Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 33
User's Guide Series

A QUASI THREE-DIMENSIONAL FINITE-DIFFERENCE GROUND-WATER FLOW MODEL WITH A FIELD APPLICATION

by
Grufron Achmad and James M. Weigle

Prepared in cooperation with the Geological Survey
United States Department of the Interior
Mayor and City Council of Ocean City
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A QUASI THREE-DIMENSIONAL FINITE-DIFFERENCE GROUND-WATER FLOW MODEL WITH A FIELD APPLICATION

by
Grufron Achmad and James M. Weigle*

ABSTRACT

This report describes a quasi three-dimensional model which was constructed from a sequence of aquifer areal-flow equations coupled by leakage terms representing flow through the confining beds. In simulating a four-aquifer system in northeastern Worcester County, Md., the model was able to reproduce the hydrographs of several observation wells with differences of less than 1 foot for 60 percent and less than 5 feet for 95 percent of the data points. The computer program of the model is given in the appendices.

* U. S. Geological Survey.

INTRODUCTION

This report describes the quasi three-dimensional ground-water flow model (quasi 3-D model) which was developed by the Maryland Geological Survey in cooperation with the U.S. Geological Survey. Included in this report is a brief discussion of the application of the model in simulating a four-aquifer system in northeastern Worcester County, Md. (fig. 1). The computer program of the model is given in the appendices.

In a multiaquifer system in which the aquifers are separated by semi-permeable layers, the evaluation of ground-water flow requires a simultaneous consideration of the entire system. Jacob (1946) introduced into the nonsteady-state flow interaction between aquifers. Since then many investigators have published various results on the subject. Among these previous works, the analytical solution of a hypothetical two-aquifer system obtained by Neuman and Witherspoon (1969a, 1969b) is of particular interest in the present work, because it was used to verify the solution obtained in this investigation (Achmad, 1979). Briefly stated the Neuman and Witherspoon analytical solution considered a wide range of aquifer properties, solved for drawdowns in the pumped and unpumped aquifers, matched the Hantush solution (1956), and was tested by finite-element modeling methods.

When using an areal model for the simulation of a multiaquifer system, the aquifers must be coupled by terms representing flow through the confining beds. Bredehoeft and Pinder (1970) and Herrera and Rodarte (1973), among others, solved the nonsteady-state vertical-flow equation, taking into account the storage of the confining bed, and used this leakage term to couple the aquifers. The finite-difference multiaquifer model documented in this report adapted a leakage term which is the nonsteady-state solution of the confining-bed vertical flow equation; the solution assumes boundary conditions that are conformable with the head distribution in adjacent aquifers. The model provides two leakage terms representing flow through the lower and upper halves of the confining bed. The alternating-direction implicit procedure (ADIP) used in the model employs a row sweep for all the aquifers, followed by a similar column sweep to complete one iteration. As indicated by Achmad (1979) the model in conjunction with the numerical technique used in this investigation yielded a reasonable match with the analytical solution of Neuman and Witherspoon (1969a, 1969b).

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QUASI 3-D MODEL

Development of Flow Equation

The quasi three-dimensional model was developed with the assumption that the flow in the aquifers is lateral and mathematically described as:

$$\frac{\partial}{\partial x} T_{xx} \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} T_{yy} \frac{\partial h}{\partial y} = S \frac{\partial h}{\partial t} + W, \qquad (1)$$

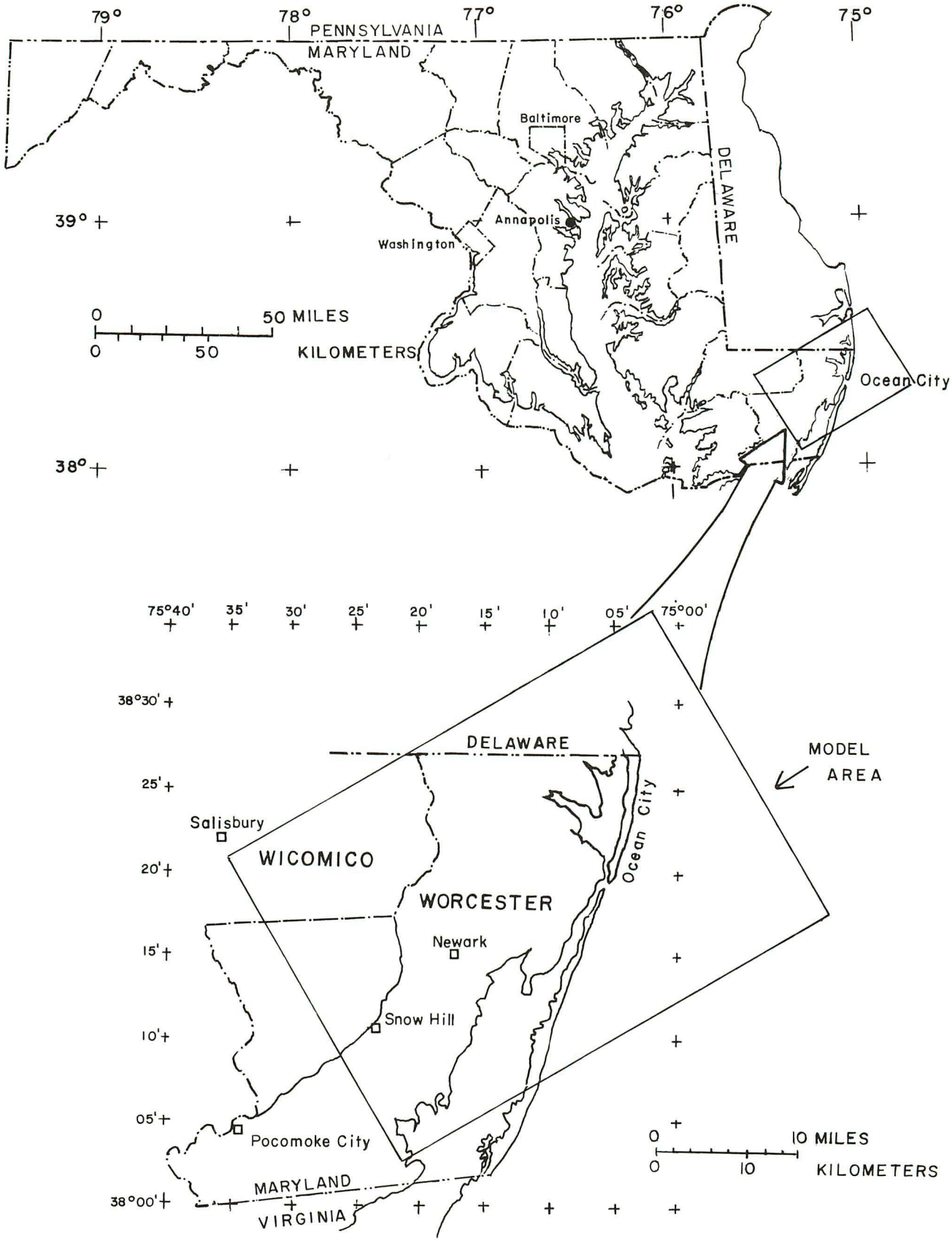

Figure 1. Location of model area

and the flow in the confining beds is vertical and mathematically described as:

$$\frac{\partial}{\partial z}(K'b')_{zz}\frac{\partial h'}{\partial z} = S'\frac{\partial h'}{\partial t}. \tag{2}$$

Under homogeneous conditions, equation 2 can be written as:

$$\frac{\partial^2 h'}{\partial z^2} = \frac{S_s'}{K'}\frac{\partial h'}{\partial t}. \tag{3}$$

Furthermore, by assuming that the head distribution in the confining bed is bounded by the head of the adjacent aquifers (h_{a_1} and h_{a_2}) and that initially the head in the confining bed is in equilibrium condition (h'^0), the boundary conditions governing equation 3 can be stated as:

$$\begin{aligned} h'(z, 0) &= h'^0, \\ h'(0, t) &= h_{a_1}, \\ h'(b, t) &= h_{a_2}. \end{aligned} \tag{4}$$

Solving the boundary value problem of equations 3 and 4, the head distribution in the confining bed can be described by the following equations:

$$\begin{aligned} h'(z, t) = h_{a_1} &+ \left(\frac{h_{a_2} - h_{a_1}}{b'}\right) z \\ &+ \frac{2}{\pi}(h^0_{a_1} - h_{a_1}) \sum_{n=1}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi}{b'} z\right) e^{-\lambda_n^2 t} \\ &- \frac{2}{\pi}(h^0_{a_2} - h_{a_2}) \sum_{n=1}^{\infty} \frac{1}{n} \cos(n\pi) \sin\left(\frac{n\pi}{b'} z\right) e^{-\lambda_n^2 t}, \end{aligned} \tag{5}$$

where

$$\lambda_n^2 t = n^2 \pi^2 \frac{K'}{S_s'} \frac{1}{b'^2} t.$$

The amount of flux resulting from the head distribution $h'(z, t)$ in the confining bed is:

$$q(z, t) = -K'\left(\frac{dh'}{dz}\right),$$

or

$$\begin{aligned} q(z, t) = -\Bigg\{ &\frac{K'}{b'}(h_{a_2} - h_{a_1}) \\ &+ \frac{2K'}{b'}(h^0_{a_1} - h_{a_1}) \sum_{n=1}^{\infty} \cos\left(\frac{n\pi}{b'} z\right) e^{-\lambda_n^2 t} \\ &- \frac{2K'}{b'}(h^0_{a_2} - h_{a_2}) \sum_{n=1}^{\infty} \cos(n\pi) \cos\left(\frac{n\pi}{b'} z\right) e^{-\lambda_n^2 t} \Bigg\}. \end{aligned} \tag{6}$$

The two leakage terms resulting from equation 6 are q_{top}, evaluated at $z = 0$; and q_{bottom}, evaluated at $x = b$. A more detailed description of the approximate solution of equations 5 and 6 is given by Achmad (1979).

Following the conditions described above, the flow equation for each aquifer becomes:

$$\frac{\partial}{\partial x} T_{xx} \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} T_{yy} \frac{\partial h}{\partial y} + q_{\text{bottom}} - q_{\text{top}} = S\frac{\partial h}{\partial t} + W. \tag{7}$$

Finite-Difference Approximations

The finite-difference approximation of the space derivative of the flow equation is obtained by manipulating the Taylor series expansion of function h in the vicinity of a node (x, y, z), assuming that h is continuous, and that higher-order derivatives of h with respect to x exist:

$$\begin{aligned} h(x + \Delta x, y, z) = h(x, y, z) &+ \Delta x \frac{\partial h}{\partial x} + \frac{\Delta x^2}{2!}\frac{\partial^2 h}{\partial x^2} \\ &+ \frac{\Delta x^3}{3!}\frac{\partial^3 h}{\partial x^3} + \frac{\Delta x^4}{4!}\frac{\partial^4 h}{\partial x^4} + \cdots + \frac{\Delta x^n}{n!}\frac{\partial^n h}{\partial x^n}, \end{aligned}$$

and

$$\begin{aligned} h(x - \Delta x, y, z) = h(x, y, z) &- \Delta x \frac{\partial h}{\partial x} + \frac{\Delta x^2}{2!}\frac{\partial^2 h}{\partial x^2} \\ &- \frac{\Delta x^3}{3!}\frac{\partial^3 h}{\partial x^3} + \frac{\Delta x^4}{4!}\frac{\partial^4 h}{\partial x^4} + \cdots + \frac{\Delta x^n}{n!}\frac{\partial^n h}{\partial x^n}. \end{aligned}$$

Combining these two equations and neglecting the derivatives higher than the third order (Δx^3), an approximate second order partial derivative of h with respect to x can be expressed as:

$$\frac{\partial^2 h}{\partial x^2} = \frac{h(x - \Delta x, y, z) - 2h(x, y, z) + h(x + \Delta x, y, z)}{\Delta x^2}$$

Similarly, the second order partial derivative of h with respect to y can be expanded as:

$$\frac{\partial^2 h}{\partial y^2} = \frac{h(x, y - \Delta y, z) - 2h(x, y, z) + h(x, y + \Delta y, z)}{\Delta y^2}.$$

The time derivative at a node ($x = i$, $y = j$) is approximated as follows:

$$h(i,j,z,t+\Delta t) = h_{(i,j,z,t)} + \frac{\Delta t}{1!}\frac{\partial h}{\partial t} + \frac{\Delta t^2}{2!}\frac{\partial^2 h}{\partial t^2} + \cdots + \frac{\Delta t^n}{n!}\frac{\partial^n h}{\partial x^n}.$$

Omitting the derivatives higher than the first order, a partial derivative of h with respect to time can be written as:

$$\frac{\partial h}{\partial t} = \frac{h_{(i,j,z,t+\Delta t)} - h_{(i,j,z,t)}}{\Delta t}.$$

Numerical Method

The finite-difference approximation of the partial differential equation 7 can be stated as follows:

$$\begin{aligned}
&\frac{2}{\Delta x_i}\left\{Tx_{i-\frac{1}{2},j,k}\frac{(h_{i-1,j,k}-h_{i,j,k})}{\Delta x_{i-1}+\Delta x_i} - Tx_{i+\frac{1}{2},j,k}\frac{(h_{i,j,k}-h_{i+1,j,k})}{\Delta x_i+\Delta x_{i+1}}\right\} \\
&+\frac{2}{\Delta y_j}\left\{Ty_{i,j-\frac{1}{2},k}\frac{(h_{i,j-1,k}-h_{i,j,k})}{\Delta y_{j-1}+\Delta y_j} - Ty_{i,j+\frac{1}{2},k}\frac{(h_{i,j,k}-h_{i,j+1,k})}{\Delta y_j+\Delta y_{j+1}}\right\} + q_{k,\text{bottom}} - q_{k+1,\text{top}} = \frac{S}{\Delta t}(h^{t+1}_{i,j,k} - h^{t}_{i,j,k}) \\
&\qquad + \sum_{i,j,k=1}^{n} Q(x,y,z)\delta(x-x_i)(y-y_j)(z-z_k),
\end{aligned} \tag{8}$$

where

$$q_{k,\text{bottom}} = -\left\{\frac{K'}{b'}(h_{a_k} - h_{a_{k-1}}) + \frac{2K'}{b'}(h^0_{a_{k-1}} - h_{a_{k-1}})\sum_{n=1}^{\infty}\cos(n\pi)e^{-\lambda_n^2 t} - \frac{2K'}{b'}(h^0_{a_k} - h_{a_k})\sum_{n=1}^{\infty}e^{-\lambda_n^2 t}\right\},$$

and

$$q_{k+1,\text{top}} = -\left\{\frac{K'}{b'}(h_{a_{k+1}} - h_{a_k}) + \frac{2K'}{b'}(h^0_{a_k} - h_{a_k})\sum_{n=1}^{\infty}e^{-\lambda_n^2 t} - \frac{2K'}{b'}(h^0_{k+1} - h_{a_{k+1}})\sum_{n=1}^{\infty}\cos(n\pi)e^{-\lambda_n^2 t}\right\}.$$

Simplifying in a compact algebraic form, equation 8 can be written as:

$$\begin{aligned}
&AX_{i,j,k}h_{i-1,j,k} + (-AX_{i,j,k} - CX_{i,j,k})h_{i,j,k} + CX_{i,j,k}h_{i+1,j,k} + AY_{i,j,k}h_{i,j-1,k} + (-AY_{i,j,k} - CY_{i,j,k})h_{i,j,k} + CY_{i,j,k}h_{i,j+1,k} \\
&\quad = STRM_{i,j,k}(h^{t+1}_{i,j,k} - h^{t}_{i,j,k}) + QTRM_{i,j,k} + QL1_{i,j,k}(h^0_{i,j,k-1} - h^{t+1}_{i,j,k-1}) - QL2_{i,j,k}(h^0_{i,j,k} - h^{t+1}_{i,j,k}) \\
&\quad - QL2_{i,j,k+1}(h^0_{i,j,k} - h^{t+1}_{i,j,k}) + QL1_{i,j,k+1}(h^0_{i,j,k+1} - h^{t+1,*}_{i,j,k+1}) + R_{i,j,k}(h^{t+1}_{i,j,k} - h^{t+1}_{i,j,k-1}) - R_{i,j,k+1}(h^{t+1,*}_{i,j,k+1} - h^{t+1}_{i,j,k}),
\end{aligned} \tag{9}$$

where

$$\begin{aligned}
STRM_{i,j,k} &= \frac{S}{\Delta t} \\
QTRM_{i,j,k} &= \sum_{i,j,z}^{n} Q(x,y,z)\delta(x-x_i)(y-y_j)(z-z_k), \\
QL1_{i,j,k} &= \frac{K'}{b'}\left(2\sum_{n=1}^{\infty}\cos(n\pi)e^{-n^2\pi^2 t_D}\right), \\
QL2_{i,j,k} &= \frac{K'}{b'}\left(2\sum_{n=1}^{\infty}e^{-n^2\pi^2 t_D}\right), \\
R_{i,j,k} &= \frac{K'}{b'}, \\
t_D &= \frac{K'}{S'_s b'^2}t,
\end{aligned}$$

and

$$AX_{i,j,k} = 2T_{i-\frac{1}{2},j,k}/\{(\Delta x_i + \Delta x_{i-1})\Delta x_i\},$$
$$CX_{i,j,k} = 2T_{i+\frac{1}{2},j,k}/\{(\Delta x_i + \Delta x_{i+1})\Delta x_i\}.$$

Similarly for $AY_{i,j,k}$, and $CY_{i,j,k}$.

The leakage terms, as calculated in equation 9, are made implicit in terms of head distribution in the corresponding aquifers, and are, therefore, evaluated at the same time step as the head distribution is calculated. For this purpose, at the beginning of each time step the $h^{t+1,*}_{i,j,k+1}$ term in equation 9 is estimated using a straight line head prediction (Achmad, 1973):

$$h^{t+1,*}_{i,j,k+1} = h^{t}_{i,j,k+1} + (h^{t}_{i,j,k+1} - h^{t-1}_{i,j,k+1})\frac{\Delta t_{\text{new}}}{\Delta t_{\text{old}}}.$$

The alternating direction implicit procedure (ADIP), introduced by Peaceman and Rachford (1955), is used in solving the resulting finite-difference equations. Setting up equation 9 for ADIP solution the linear algebraic equation for each axial direction calculation is the following:

For X direction calculation:

$$AX_{i,j,k}h^{t+\frac{1}{2}}_{i-1,j,k} + BX_{i,j,k}h^{t+\frac{1}{2}}_{i,j,k} + CX_{i,j,k}h^{t+\frac{1}{2}}_{i+1,j,k} = DX_{i,j,k},$$

where

$$\begin{aligned} BX_{i,j,k} &= -AX_{i,j,k} - CX_{i,j,k} - AY_{i,j,k} - CY_{i,j,k} - STRM_{i,j,k} \\ &\quad - QL2_{i,j,k} - R_{i,j,k} - QL2_{i,j,k+1} - R_{i,j,k+1}, \\ DX_{i,j,k} &= -AY_{i,j,k}h^{t}_{i,j-1,k} - CY_{i,j,k}h^{t}_{i,j+1,k} - STRM_{i,j,k}h^{t}_{i,j,k} \\ &\quad + QTRM_{i,j,k} + LTRM_{i,j,k}, \end{aligned}$$

and

$$\begin{aligned} LTRM_{i,j,k} = QL1_{i,j,k}(h^{0}_{i,j,k-1} - h^{t+1}_{i,j,k-1}) - QL2_{i,j,k}h^{0}_{i,j,k} + QL1_{i,j,k+1}(h^{0}_{i,j,k+1} - h^{t+1,*}_{i,j,k+1}) \\ - QL2_{i,j,k+1}h^{0}_{i,j,k} - R_{i,j,k}h^{t+1}_{i,j,k-1} - R_{i,j,k+1}h^{t+1,*}_{i,j,k+1}. \end{aligned}$$

For Y direction calculation:

$$AY_{i,j,k}h^{t+1}_{i,j-1,k} + BY_{i,j,k}h^{t+1}_{i,j,k} + CY_{i,j,k}h^{t+1}_{i,j+1,k} = DY_{i,j,k},$$

where

$$\begin{aligned} BY_{i,j,k} &= -AY_{i,j,k} - CY_{i,j,k} - AX_{i,j,k} - CX_{i,j,k} \\ &\quad - STRM_{i,j,k} - QL2_{i,j,k} - R_{i,j,k} - QL2_{i,j,k+1} - R_{i,j,k+1}, \end{aligned}$$

and

$$\begin{aligned} DY_{i,j,k} &= -AX_{i,j,k}h^{t+\frac{1}{2}}_{i-1,j,k} - CX_{i,j,k}h^{t+\frac{1}{2}}_{i+1,j,k} - STRM_{i,j,k}h^{t}_{i,j,k} \\ &\quad + QTRM_{i,j,k} + LTRM_{i,j,k}. \end{aligned}$$

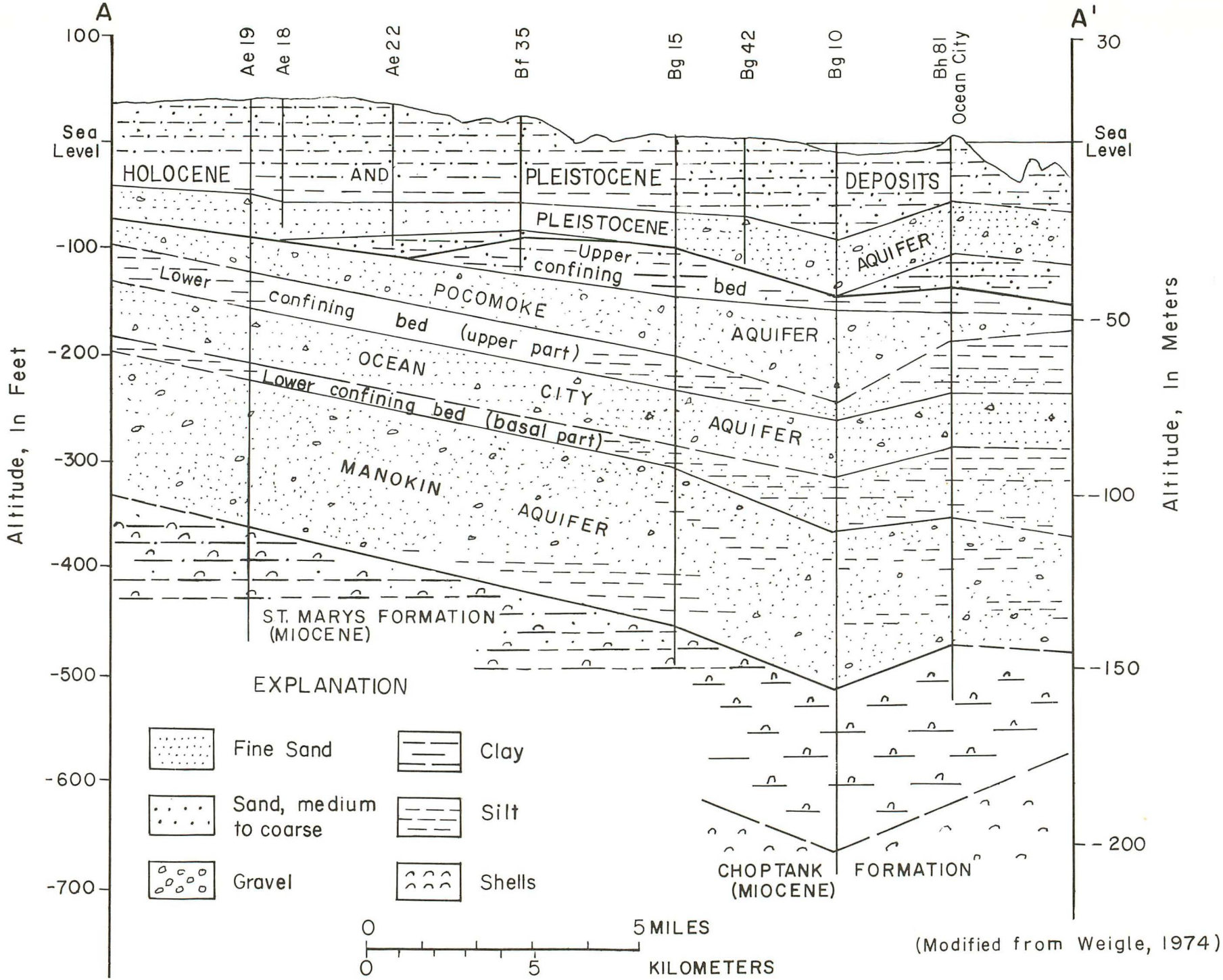

Figure 2. Schematic geologic section A-A'

In solving the flow equation for a two-dimensional one-layer model the ADIP makes an alternate row and column calculations for all the nodes in that layer. In a multiaquifer system, the flow equation must be solved simultaneously for all the aquifers. In order to simultaneously solve the finite-difference equations the row and column calculations were performed alternately so that the entire system of nodes were covered at each time step. In this manner, the row calculation sweeps the nodes in the first aquifer, proceeds with the ones in the second, and finishes with the ones in the last aquifer; and the column calculation sweeps the nodes in the first, proceeds with the ones in the second, and finishes with the ones in the last aquifer. The procedures are repeated until the closure criterion is met.

FIELD APPLICATION

Description of Aquifer System

The 450-ft (137 m) thick fresh ground-water reservoir in northeastern Worcester County, Maryland contains a series of interconnected aquifers of Miocene, Pliocene (?) and Pleistocene age. Seasonally heavy pumping of 5 Mgal/d (18,925 m^3/d) produces a maximum 30-ft (9 m) areal drawdown in the pumped aquifer and a 5-ft (1.5 m) areal drawdown in the adjacent aquifers. The reduction of pumping during the off-season, combined with recharge from precipitation, results in annual recovery of water levels. The aquifer system is best represented as a multiaquifer system.

The aquifers under study are the four uppermost aquifers, which supply the water needed for farming, domestic use, and public utilities in Worcester County. In that vicinity, the aquifers are known as the Pleistocene, Pocomoke, Ocean City, and Manokin aquifers (fig. 2).

Finite-Difference Grid

The model area, which includes only a portion of the entire aquifer system, covers 875 mi^2 (2266 km^2) and is divided into 35 × 25 elemental blocks of 1-square mile each (fig. 3). Specific conditions are assigned to the boundary nodes of the model to represent the hydrologic setting.

Constant-head conditions are assigned to the boundary nodes at the northwestern corner of the model, which represents a part of the outcrop area of the aquifers. The southeastern boundary nodes are made constant head nodes as they are assumed to represent a part of the aquifer zone of ocean discharge. These assignments establish hydraulic gradient and provide for subsurface flow in the model. The other boundary nodes, which define the aquifer limits or represent flow divides, are assigned no-flow boundary conditions.

The simulation of flow in the aquifers and of leakage between the aquifers creates a recharge-discharge mechanism in the model, and simulates the field conditions.

Source of Data

The data used for the model were derived mostly from recently published reports. Prepumping potentiometric and transmissivity matrices were derived from maps prepared by Weigle (1974). Data were extrapolated to cover the complete model area and an average value was estimated for each element of the finite-difference grid.

Storage coefficients were selected from values reported by Cushing, Kantrowitz, and Taylor (1973). The confining-bed hydraulic characteristics were derived from laboratory tests of Miocene clays cored at Ocean City in 1976 (data filed in U.S. Geological Survey Maryland District Office) and from field and laboratory results obtained at Salisbury (Wolff, 1970).

Model Calibration

Calibration was achieved by adjusting values of the hydraulic characteristics used in the model until the model could reproduce the prepumping potentiometric surface, and match the measured hydrographs of the observation wells.

In general, the amount of change of parameter values permitted was based on: (1) the reliability of the data, (2) the significance of the parameter, and (3) the range of values normally encountered in the field.

Only minor adjustments were allowed in the water levels of the model in the process of duplicating the prepumping potentiometric surfaces. These adjustments consisted of equating the water levels of the Pocomoke aquifer in its subcrop area with the water levels of the Pleistocene aquifer and smoothing the water levels in the Manokin aquifer at the southwest corner of the model. The simulated prepumping water levels are shown in figures 4 to 7.

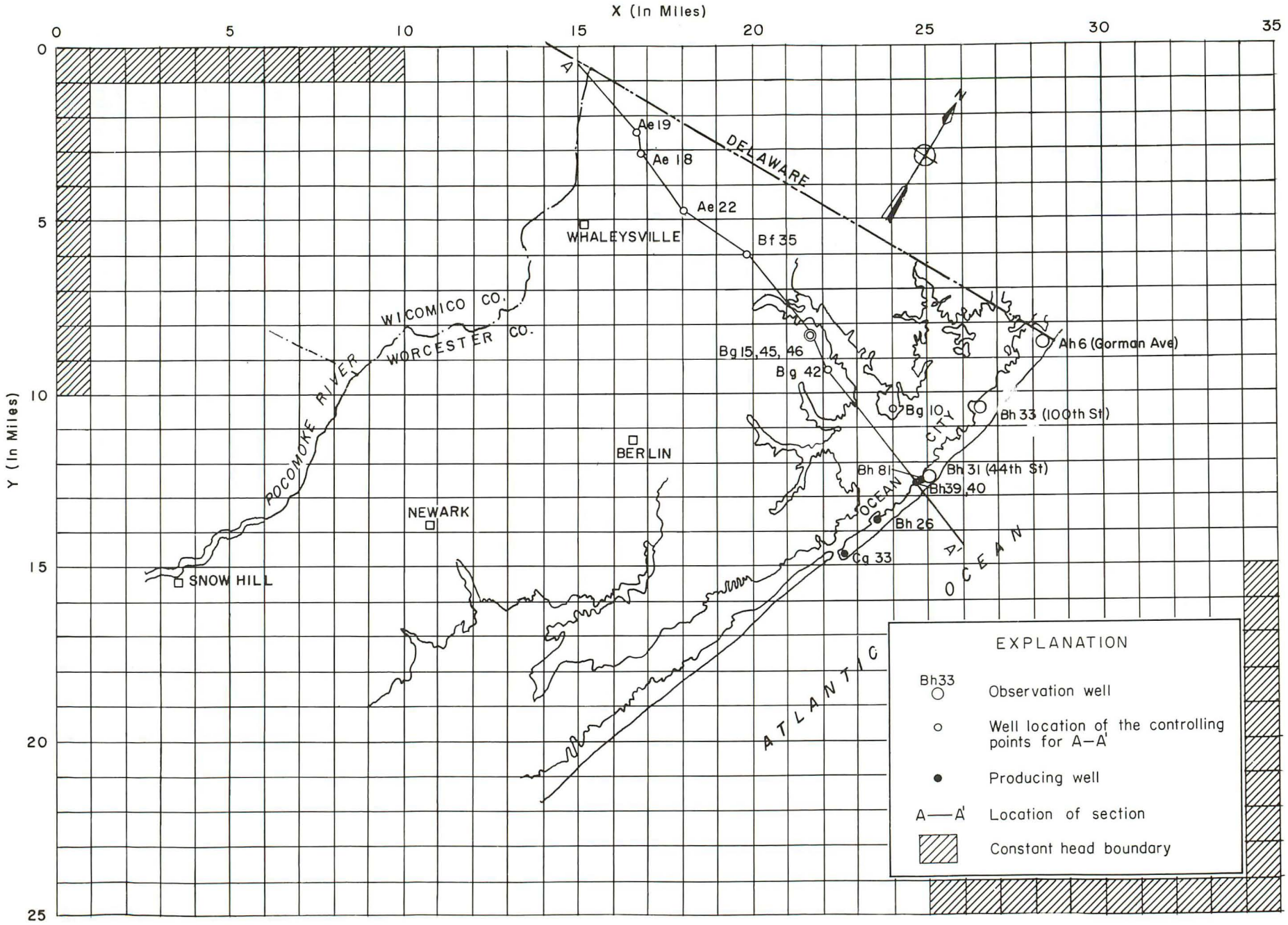

Figure 3. Grid system and location of geologic section A-A′

During calibration, only minor adjustments were permitted in the transmissivity matrices because the transmissivity and water-level data were considered the most reliable of the model input parameters. The calibrated transmissivity values are shown in figures 8 to 11.

The aquifers were regarded as having a uniform storage coefficient (S) and a single value was assigned to each aquifer. After several trial runs, it was found that the storage coefficient values that gave the best results are as follows: $S_{\text{Manokin}} = 0.00012$, $S_{\text{Ocean City}} = 0.00009$, $S_{\text{Pocomoke}} = 0.00012$, and $S_{\text{Pleistocene}} = 0.0015$.

The vertical hydraulic conductivity and the specific storage of the confining beds are the least known parameters. Values for vertical conductivity and specific storage of a Miocene clay from Salisbury, Maryland have been reported by Wolff (1970). The values are as follows: hydraulic conductivity ranged from 2.8×10^{-5} to 5.7×10^{-3} ft/day (8.5×10^{-6} to 1.7×10^{-3} m/day); specific storage ranged from 0.3×10^{-4} to 1.8×10^{-4} ft^{-1} (9.8×10^{-5} to 5.9×10^{-4} m^{-1}). Laboratory tests made in 1976 on a Pleistocene clay sample from Ocean City (filed in U.S. Geological Survey Maryland District Office) indicated a vertical conductivity of 9.0×10^{-5} ft/day (3.0×10^{-5} m/day). However, simulation runs indicated that the most satisfactory results were obtained by using the following values:

> $S'_s = 0.4 \times 10^{-4}$ ft^{-1} (0.1×10^{-4} m^{-1}), K'_{vertical} for confining bed on top of Pocomoke and Ocean City aquifer $= 3.6 \times 10^{-5}$ ft/d (1.1×10^{-5} m/d), and K'_{vertical} for confining bed on top of Manokin $= 1.9 \times 10^{-3}$ ft/d (5.8×10^{-4} m/d).

Using the hydraulic parameters described above, the production performance of the multiaquifer system at Ocean City was simulated for a 2-year period of 1971 and 1972. The model simulated the effect of pumping from the Ocean City aquifer at four pumping centers in Ocean City (table 1). The pumping was not uniformly distributed throughout the year; it varied seasonally, reflecting the fact that Ocean City is a resort area.

TABLE 1. RATE OF WATER WITHDRAWAL FROM WELLS SCREENED IN THE OCEAN CITY AQUIFER
(In Million Gallons Per Day)

	1971				1972			
	well 1	2	3	4	well 1	2	3	4
Jan	0.385	0.081	0.183	0.610	0.622	0.0	0.242	0.610
Feb	.0	.402	.226	.610	.553	.0	.340	.610
Mar	.0	.444	.259	.920	.451	.0	.318	.920
Apr	.0	.735	.441	.920	.675	.0	.493	.920
May	.221	.874	.516	.920	1.041	.146	.627	.920
Jun	.615	1.077	.907	.920	1.118	.578	.916	.920
Jul	1.089	1.289	1.408	.920	1.374	1.370	1.576	.920
Aug	1.061	1.499	1.745	.920	1.510	1.423	1.915	.920
Sep	.582	.814	.879	.920	.991	.799	.965	.920
Oct	.161	.528	.414	.920	.818	.0	.532	.920
Nov	.263	.236	.367	.610	.601	.0	.516	.610
Dec	.447	.0	.251	.610	.618	.0	.518	.610

Explanation:
well 1 = Cg 33, South-end
well 2 = Bh 26, 14th and 15th Street
well 3 = Bh 81, 44th Street
well 4 = Bh 39 and 40, Convention Hall
(see figure 3 for well location)

The two-year period of pumping was divided into 25 pumping intervals of one month each. Starting with an initial time step of 24 hours and using a multiplication factor of 1.2, the time step was gradually increased up to 300 hours where it was then kept constant. With this time step, the ADIP converged to a solution within two, or at the most three iterations, which is considered reasonable and effective.

A comparison of simulated hydrographs with records of observation wells is shown in figure 12. The starting head used in the simulation is the prepumping water level, upon which the 1971 and 1972 monthly pumpage was stressed. For places further away from the pumping center like Ah 6, Bg 15, and Bg 16, the prepumping and 1971 water levels are about the same. However, at places nearby a pumping center, as for example Bh 33 and Bh 31,

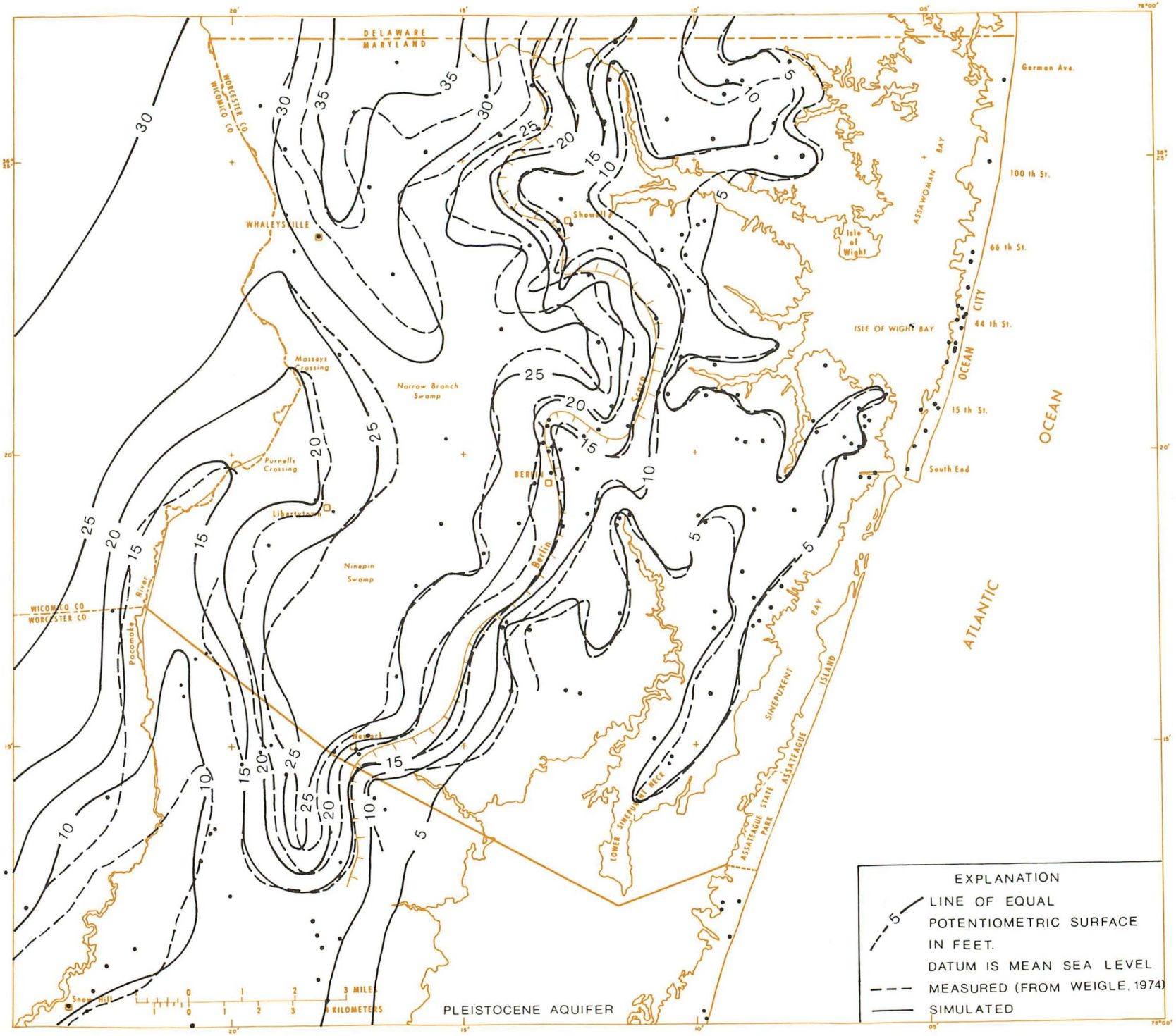

Figure 4. Potentiometric surface of Pleistocene aquifer, prepumping condition

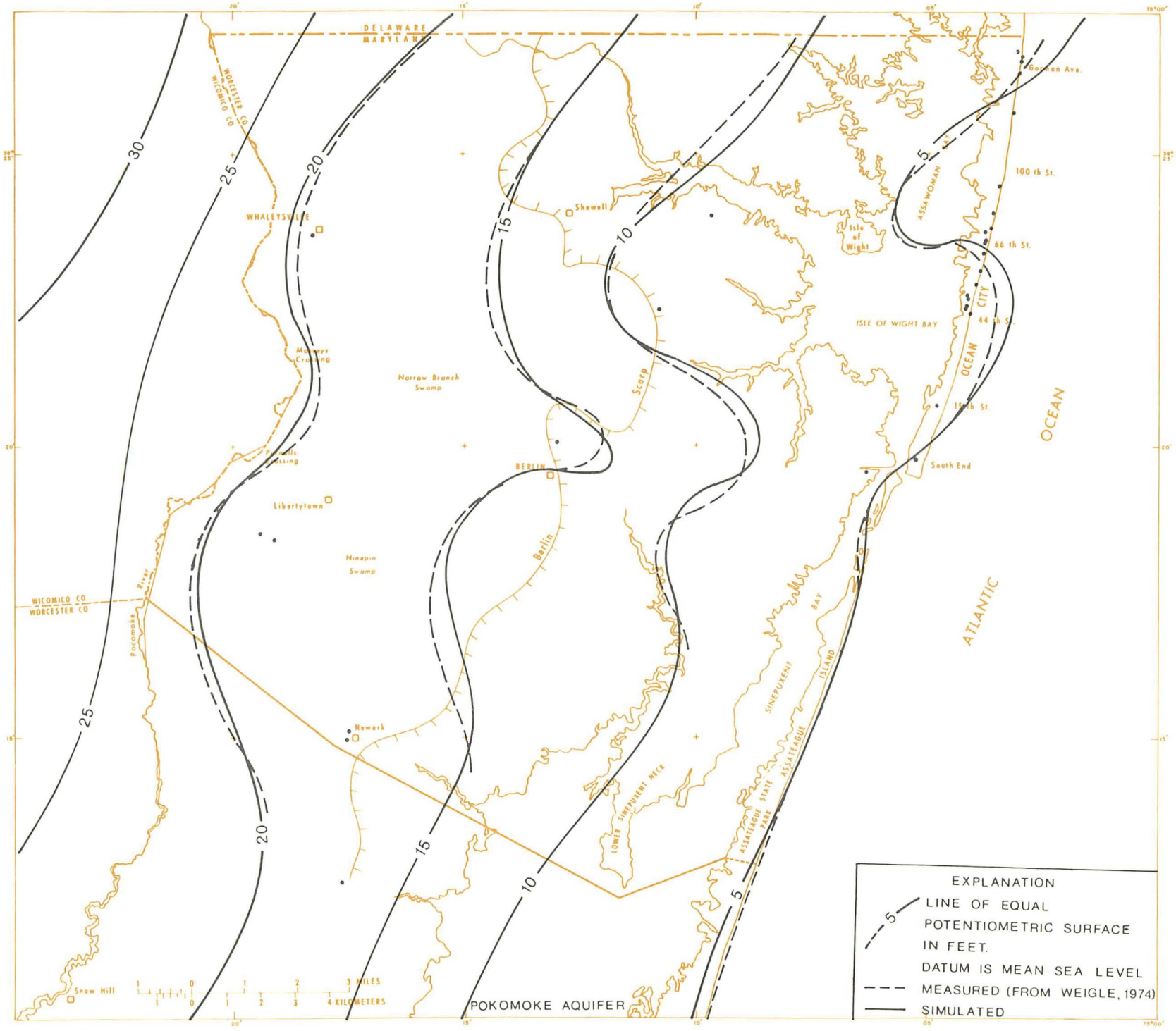

Figure 5. Potentiometric surface of Pocomoke aquifer, prepumping condition

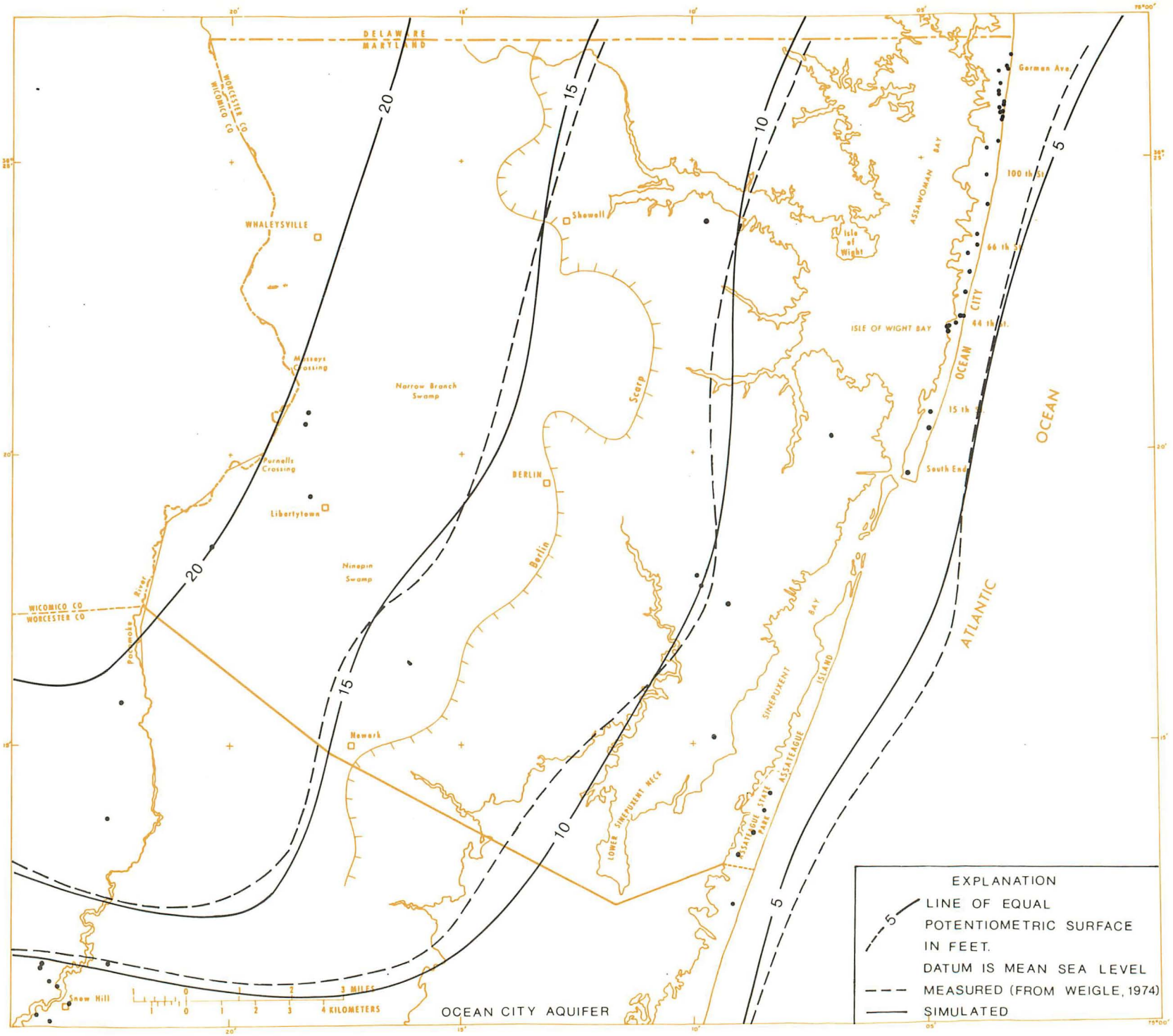

Figure 6. Potentiometric surface of Ocean City aquifer, prepumping condition

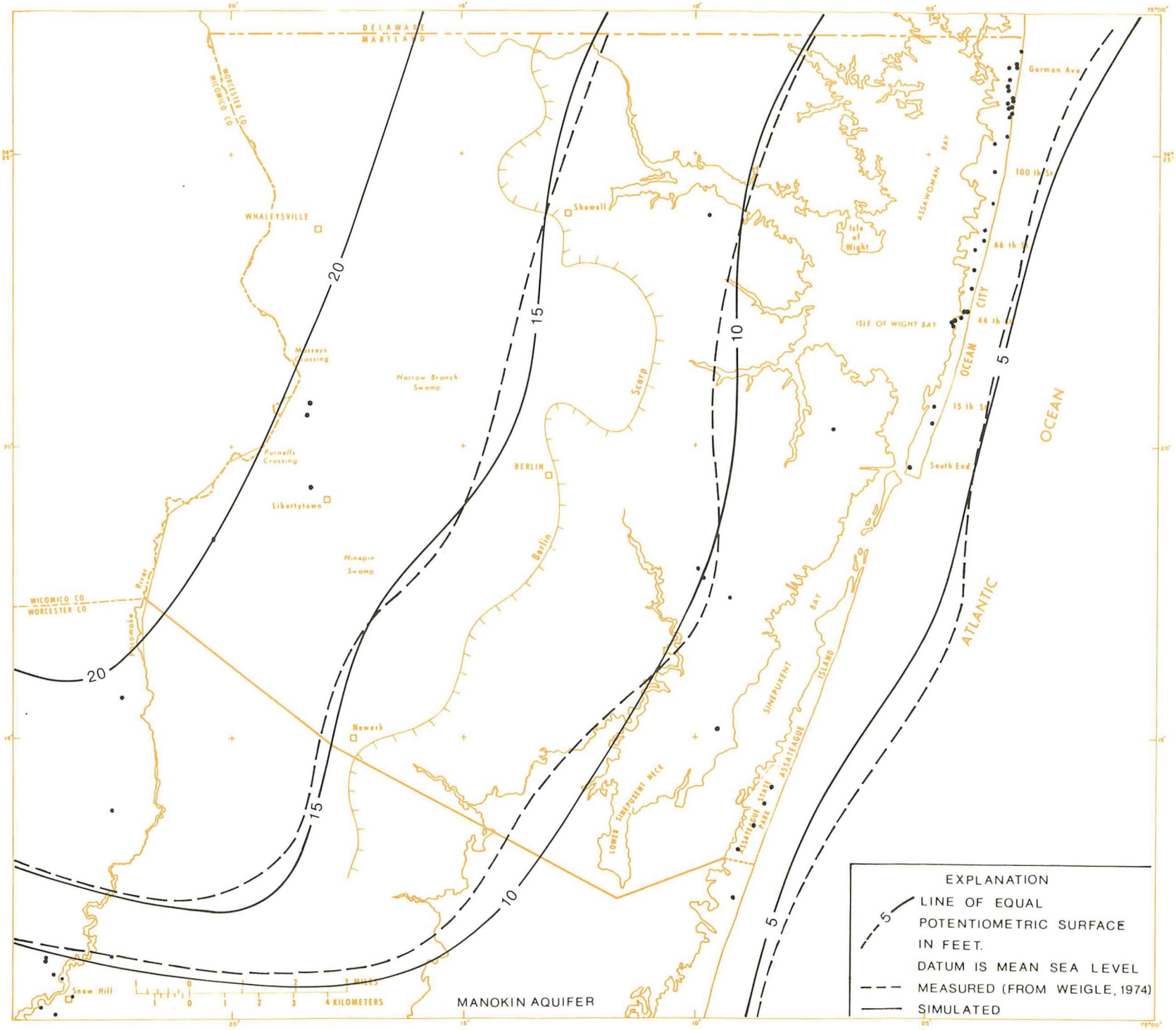

Figure 7. Potentiometric surface of Manokin aquifer, prepumping condition

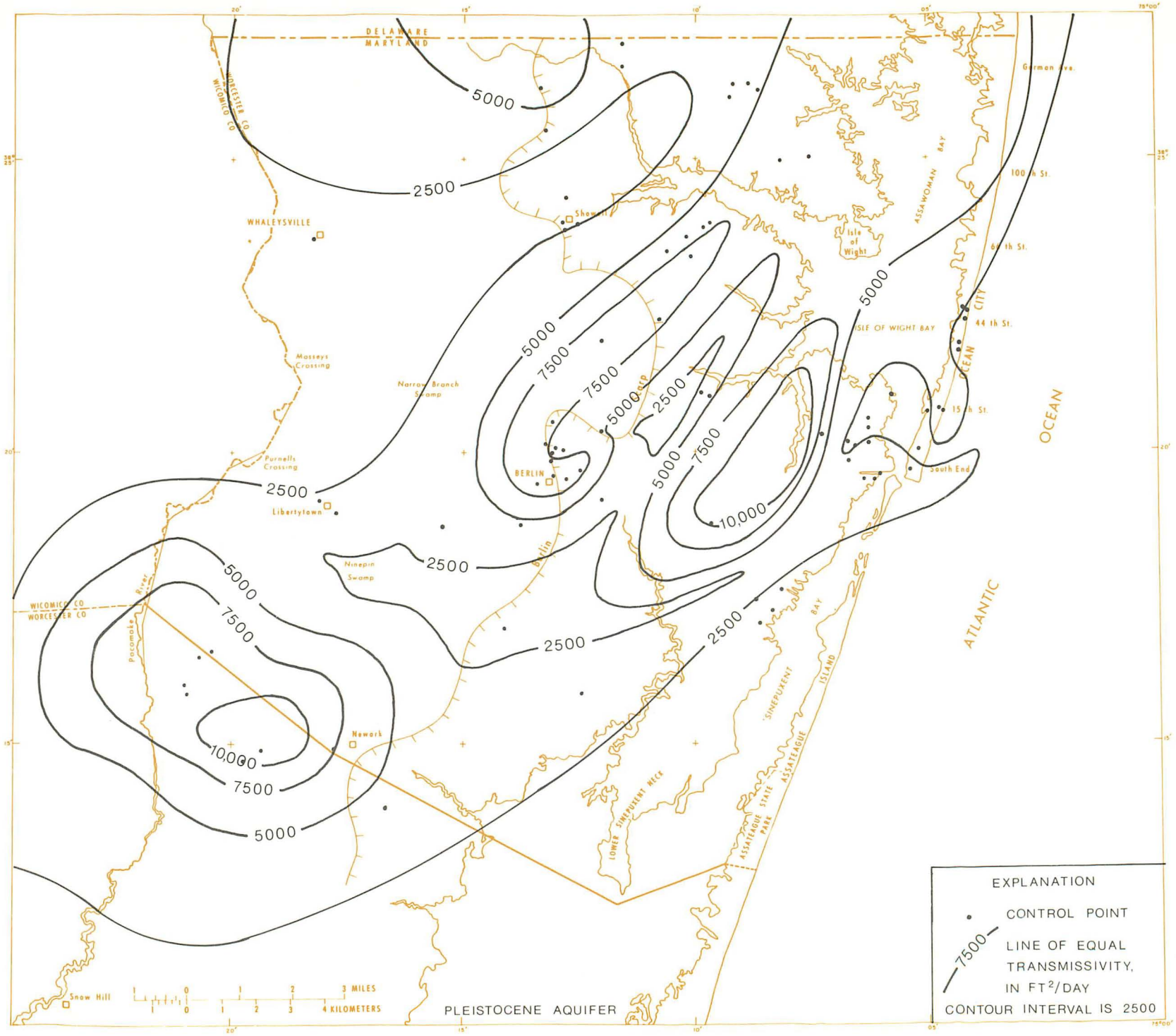

Figure 8. Transmissivity of Pleistocene aquifer used in the model

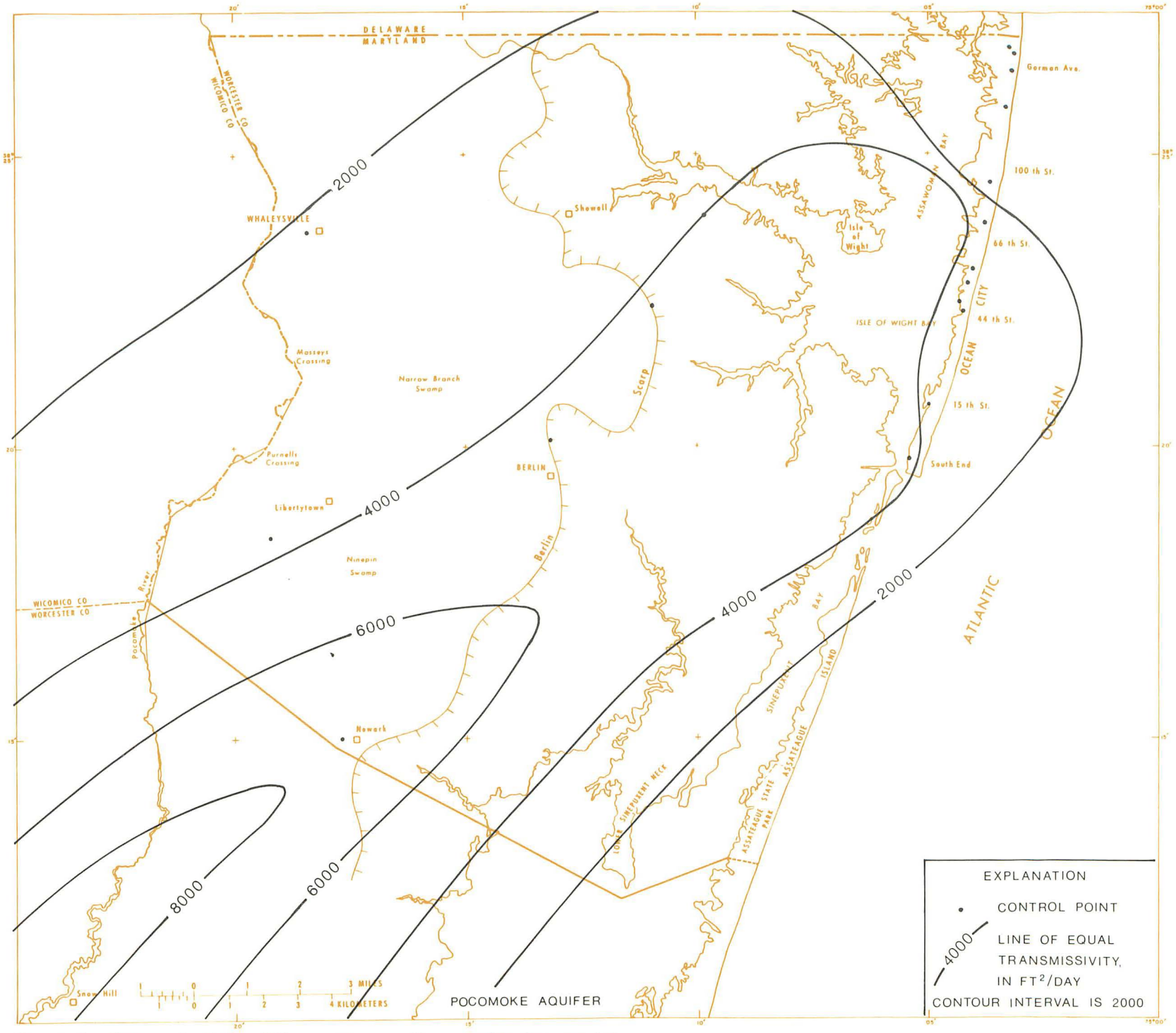

Figure 9. Transmissivity of Pocomoke aquifer used in the model

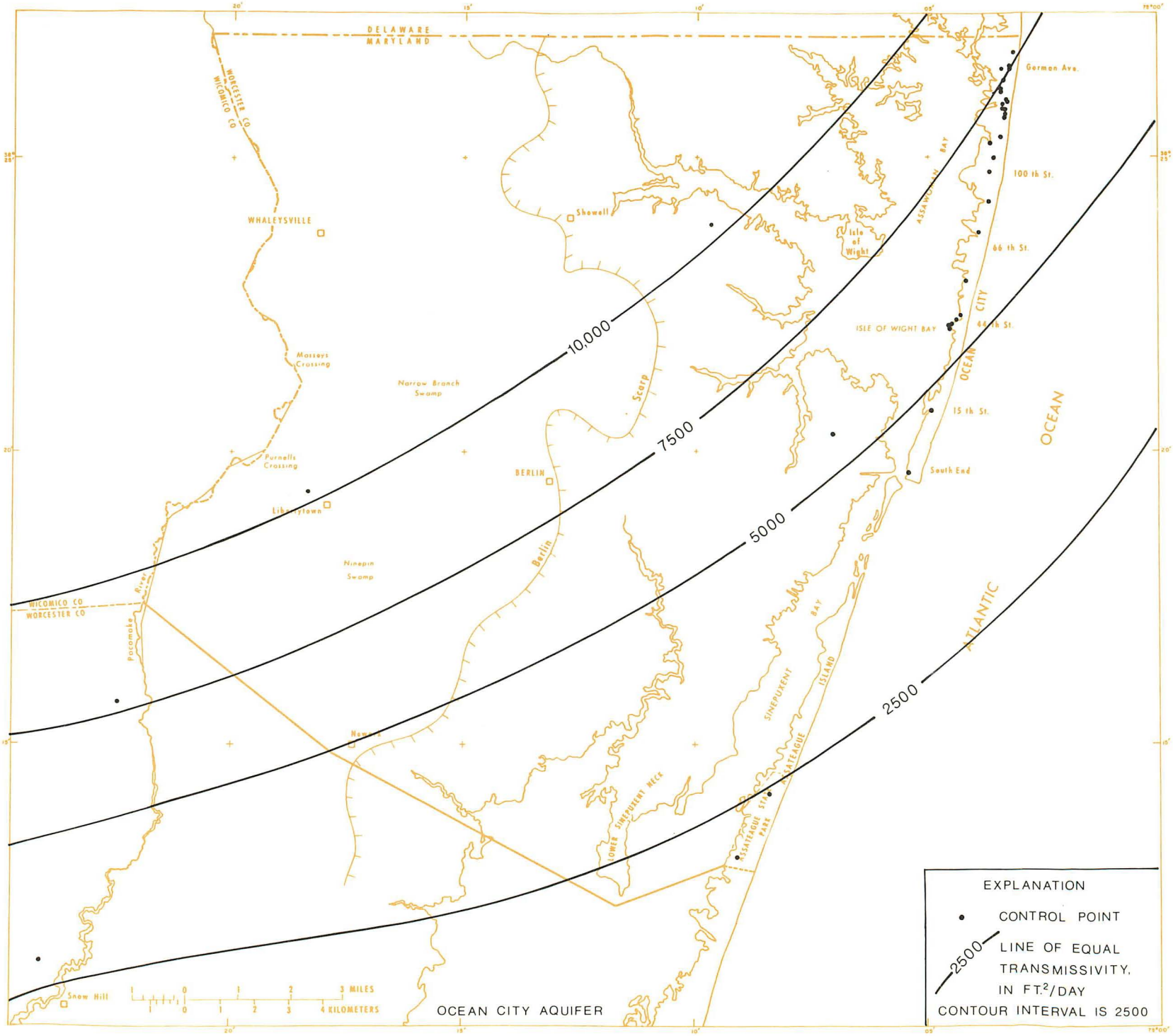

Figure 10. Transmissivity of Ocean City aquifer used in the model

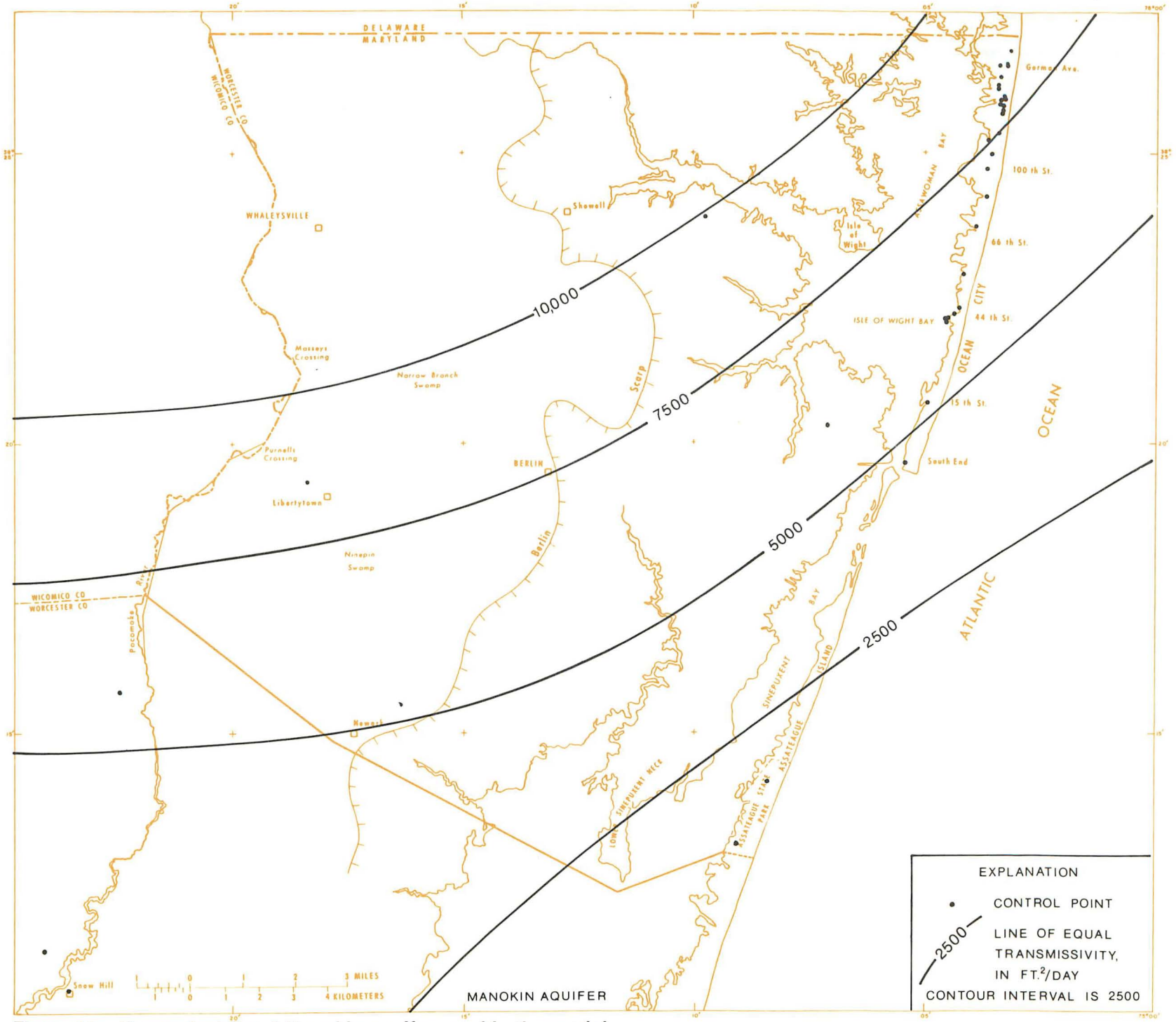

Figure 11. Transmissivity of Manokin aquifer used in the model

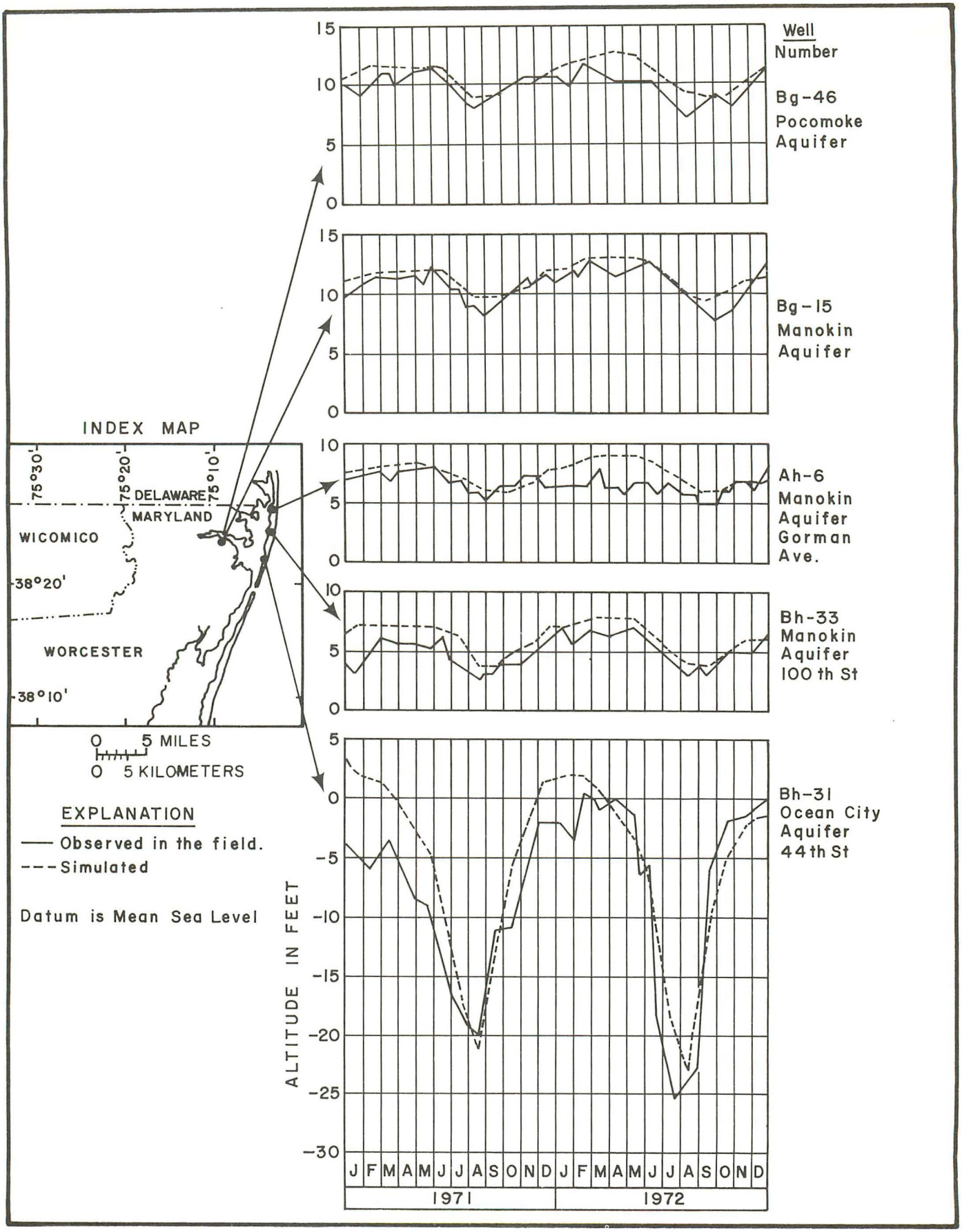

Figure 12. Hydrographs of observation wells

the differences are between 3 to 6 feet each. This accounts for the offset between the observed and simulated hydrographs at the start of the simulation period.

A report detailing the use of the developed quasi 3-D model to predict future ground water trends in the northeastern Worcester County, Md. is currently in preparation by the authors (Weigle and Achmad, 1980).

CONCLUSIONS

A quasi three-dimensional model was developed and used to simulate the four-aquifer system in northeastern Worcester County, Maryland. Over a two-year simulation period, the model was capable of generating a potentiometric head distribution that adequately reproduced hydrographs from several observation wells screened in the pumped aquifer, as well as in other aquifers (Manokin, Pocomoke, Pleistocene). The simulated hydrographs match the ones measured in the field with differences of less than 1 foot for 60 percent and less than 5 feet for 95 percent of the data points.

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APPENDIX I

Notation

A	cross-sectional area of flow (L^2);
b	saturated thickness (L);
D	right-hand side of the flow equation;
$AX, AY, AZ, CX, CY, CZ, BX, BY, DX, DY$	coefficients of the finite-difference equation;
h	altitude of water level (L);
K	hydraulic conductivity (LT^{-1});
q	unit discharge through the entire thickness of aquifer (L^3T^{-1});
S	storage coefficient (dimensionless);
S_s	specific storage (L^{-1});
t	time (T);
T	transmissivity (L^2T^{-1});
W	source term (LT^{-1});
$\Delta x, \Delta y, \Delta z$	space increments, in the X, Y, and Z directions (L);
Δt	time increment (T);
Subscript	
$a1, a2$	aquifer 1, aquifer 2;
i, j, k	position index, in the X, Y, and Z directions;
xx, yy, zz	primary x, y, and z directions.
Superscript	
0	initial time level;
$t - 1$	previous time level;
t	current time level;
$t + 1$	next time level;
$n - 1$	previous iteration level;
n	current iteration level;
$n + 1$	next iteration level;
$'$	confining bed index.

APPENDIX II

COMPUTER PROGRAM

Main Program

The program was kept simple by writing it as a single main program. In this manner the program can be easily expanded to account for specific problems to be modeled.

For each program, the program has to be dimensioned specifically. The hydraulic parameters are dimensioned according to the number of nodes in the system. The layers are numbered sequentially starting with a smaller number for the top layer and increasing to a higher number for a lower layer.

There are three main loops in the calculation process: (1) time-period loop; (2) time-step loop; and (3) iteration loop. The iteration loop is completed as soon as the calculated water levels of two consecutive iterations are less than the closure criterion. The magnitude of the closure criterion determines the accuracy of the results, and a value of 0.01 is considered sufficient.

Input Data

This part of the main program initializes and defines the hydraulic parameters of the aquifer system. In addition to the values of the hydraulic parameters, the size of the time step, the total period of simulation, the number of time steps, and the calculation options must be read in. The program was written in consistent units with hour as the time unit.

A constant-head boundary node is coded with a negative storage coefficient value, and the program assigns to these nodes a very large storage coefficient (1×10^{40}).

Coefficients Calculations

In order to reduce computational efforts, all coefficients of the finite-difference equations that are independent of time are calculated outside the time-period loop and stored. For this reason, the A and the C coefficients are stored as well as parts of the B and the D coefficients. The leakage coefficients are time dependent, and they are reevaluated for each time step.

Mass Balance

The mass-balance routine computes the amount of flux coming into and going out of the system as pumping stress is applied. The volume released from storage is considered to be a source. The volume pumped is classified as a discharge.

Subroutine Map

This subroutine has been adapted from the Trescott model (1975). This routine will print maps of potentiometric head distribution. By specifying the parameter SCALE, the unit length used in the model is changed to the unit length used in the map. The parameter DINCH is the number of map units per inch. The parameter SPACNG is the multiplication factor for adjusting the value plotted on the map to the value of each node in the model.

In case of the Ocean City model, the parameters: SCALE, DINCH, and SPACNG, and the aquifer names are set by program.

APPENDIX III

PROGRAM LISTING

```
C     PROGRAM LISTING                                                   MN001000
C                                                                       MN001010
C                                                                       MN001020
C                                                                       MN001030
C     QUASI THREE-DIMENSIONAL FINITE-DIFFERENCE                         MN001040
C     GROUND-WATER FLOW MODEL                                           MN001050
C     USED TO SIMULATE THE MULTIAQUIFER SYSTEM                          MN001060
C     IN NORTHEASTERN WORCESTER COUNTY, MARYLAND                        MN001070
C                                                                       MN001080
C                                                                       MN001090
C                                                                       MN001100
C     JULY  1978                                                        MN001110
C                                                                       MN001120
C                                                                       MN001130
C     ARA            SURFACE AREA OF AN ELEMENT                         MN001140
C     ATIME          PREVIOUS SIMULATION TIME                           MN001150
C     AX,AY,AZ       A-COEFFICIENTS IN THE X, Y, AND Z DIRECTIONS       MN001160
C     B,G,W          ADI PARAMETERS, THOMAS ALGORITHM                   MN001170
C     BX             B-COEFFICIENT                                      MN001180
C     CDLT           MULTIPLICATION FACTOR FOR THE TIME-STEP SIZE       MN001190
C     CHDT           RECHARGE FROM CONSTANT HEAD                        MN001200
C     CHST           DISCHARGE FROM CONSTANT HEAD                       MN001210
C     CLNT           DISCHARGE FROM LEAKAGE                             MN001220
C     CLST           RECHARGE FROM LEAKAGE                              MN001230
C     CM             CONFINING BED THICKNESS                            MN001240
C     CX,CY,CZ       C-COEFFICIENTS IN THE X, Y, AND Z DIRECTIONS       MN001250
C     DD             TOTAL OF THE RIGHT-HAND SIDE OF THE FINITE DIFFERENCEMN001260
C                     EQUATION                                          MN001270
C     DELTA          SIZE OF TIME STEP                                  MN001280
C     DTN            NEW TIME INCREMENT                                 MN001290
C     DTO            OLD TIME INCREMENT                                 MN001300
C     ERROR          CLOSURE CRITERIA                                   MN001310
C     FC             MULTIPLICATION FOR GRID SPACING                    MN001320
C     FCT            MULTIPLICATION FACTOR FOR TRANSMISSIVITY           MN001330
C     H (HI,HO,      WATER LEVEL (INITIAL-, PREVIOUS-, CURRENT          MN001340
C      HC,HF)         TIME STEP, PREVIOUS ITERATION LEVEL)              MN001350
C     IDDN           PARAMETER CONTROLLING THE PRINTING OF DRAWDOWNS    MN001360
C     IHDN           PARAMETER CONTROLLING THE PRINTING OF HEADS        MN001370
C     IITER          MAXIMUM NUMBER OF ITERATION                        MN001380
C     IMAP           PARAMETER CONTROLLING THE PRINTING OF MAP          MN001390
C     IPCH           CONTROL CODE TO PUNCH HEAD FOR CONTINUATION RUN    MN001400
C     IREP           CONTROL CODE FOR CONTINUATION RUN                  MN001410
C     ISS            CONTROL CODE FOR STEADY-STATE RUN                  MN001420
C     IWCH           CONTROL CODE TO PRINT OUT HEAD FOR CONTINUATION RUN MN001430
C     IWMB           CONTROL CODE TO PRINT OUT MATERIAL BALANCE         MN001440
C     IWRT           CONTROL CODE TO PRINT OUT INPUT DATA MATRICES      MN001450
C     KP             COUNTING NUMBER FOR CURRENT TIME PERIOD            MN001460
```

```
C     KPM1          COUNTING NUMBER FOR THE PREVIOUS TIME STEP          MN001470
C     NC            NUMBER OF COLUMNS                                   MN001480
C     NL            NUMBER OF LAYERS                                    MN001490
C     NR            NUMBER OF ROWS                                      MN001500
C     NPER          NUMBER OF TIME PERIODS                              MN001510
C     NWEL          TOTAL NUMBER OF WELLS                               MN001520
C     NUMT          TOTAL NUMBER OF TIME PERIOD                         MN001530
C     PUMPT         VOLUME PUMPED                                       MN001540
C     Q             WELL PRODUCTION RATE                                MN001550
C     QL            COEFFICIENT OF TRANSIENT LEAKAGE                    MN001560
C     R             COEFFICIENT OF CONSTANT LEAKAGE                     MN001570
C     RATE          CONDUCTIVITY OF THE CONFINING BED                   MN001580
C     RADIUS        WELL RADIUS                                         MN001590
C     SC            STORAGE COEFFICIENT OF THE AQUIFER                  MN001600
C     SS            SPECIFIC STORAGE OF THE CONFINING BED               MN001610
C     STORT         VOLUME FROM STORAGE                                 MN001620
C     TLNT          RECHARGE FROM TRANSIENT LEAKAGE                     MN001630
C     TLST          DISCHARGE FROM TRANSIENT LEAKAGE                    MN001640
C     TS            TRANSMISSIVITY                                      MN001650
C     X,Y,Z         INCREMENTS IN THE X, Y, AND Z DIRECTIONS            MN001660
C                                                                       MN001670
C                                                                       MN001680
C                                                                       MN001690
C                                                                       MN001700
C                                                                       MN001710
      DIMENSION HI(35,25,4),HC(35,25,4),HF(35,25,4),HO(35,25,4),        MN001720
     *          DDN(35,25,4),DDNN(35,25,4),                             MN001730
     *          AX(35,25,4),CX(35,25,4),AY(35,25,4),CY(35,25,4),        MN001740
     *          BX(35,25,4),D(35,25,4),                                 MN001750
     *          B(35,4),G(35,4),ARA(35,25),NWR(80,2),Nw(4),             MN001760
     *          TS(35,25,4),R(35,25,4),SS(4),RATE(4),SC(4),CM(4),       MN001770
     *          SF2(35,25,4),RADIUS(35,25,4),QRE(35,25,4),QL(35,25,4),  MN001780
     *          CHDT(4),CHST(4),PUMPT(4),CFLUXT(4),TOTL1(4),TOTL2(4),   MN001790
     *          SUMR(4),DIFF(4),PERCNT(4),TITLE(40),STORT(4),CLST(4),   MN001800
     *          CLNT(4),TLST(4),TLNT(4),ESM(4),FCT(4)                   MN001810
C                                                                       MN001820
      DIMENSION QL1(35,25,4),QL2(35,25,4),SD(4),QRET(4)                 MN001830
      COMMON    H(35,25,4),SF1(35,25,4),X(35),Y(25),                    MN001840
     *          Q(35,25,4),NC,NR,NL,IKP                                 MN001850
C                                                                       MN001860
C                                                                       MN001870
      DATA      PI/3.1415926535898/,TOL/174.673/,BNUM/1E40/,            MN001880
     *          BNUM1/.5E40/                                            MN001890
C                                                                       MN001900
      CALL ERRSET(208,256,-1,1)                                         MN001910
C                                                                       MN001920
C                                                                       MN001930
C     DATA INPUT                                                        MN001940
```

```
C
      READ(5,180) TITLE
      READ(5,210) NC,NR,NL,NPER,DELTA,ERROR,ATIME
     *  (K,SC(K),RATE(K),SS(K),CM(K),KK=1,NL)
C
C
      READ(5,340)IITER,IHDN,IDDN,IWRT,ISS,IREP,IPCH,IMAP,IWMB,IWCH
      DO 100 K=1,NL
      READ(5,310) STORT(K),CHDT(K),CHST(K),PUMPT(K)
  100 READ(5,310) CLST(K),CLNT(K),TLST(K),TLNT(K)
      READ(5,320) FC
      READ(5,110)(X(I),I=1,NC)
      READ(5,110)(Y(J),J=1,NR)
  110 FORMAT(20G4.0)
      DO 120 K=1,NL
      READ(5,320) FCT(K)
      DO 120 J=1,NR
  120 READ(5,300) (TS(I,J,K),I=1,NC)
      DO 130 K=1,NL
      DO 130 J=1,NR
  130 READ(5,300) (HI(I,J,K),I=1,NC)
      DO 160 K=1,NL
      DO 140 J=1,NR
      TS(1,J,K)=0.
  140 TS(NC,J,K)=0.
      DO 150 I=1,NC
      TS(I,1,K)=0.
  150 TS(I,NR,K)=0.
  160 CONTINUE
C
      WRITE(6,190) TITLE
      WRITE(6,230) NR,NC,NL,NPER,ICSPR,DELTA,ERROR,ATIME
      WRITE(6,240) FC,(X(I),I=1,NC)
      WRITE(6,250) (Y(J),J=1,NR)
      WRITE(6,260)
      WRITE(6,270)
      DO 170 K=1,NL
  170 WRITE(6,280) (RATE(K),SS(K),CM(K))
      WRITE(6,290)
      WRITE(6, )
      WRITE(6,330) (KK,SC(KK),KK=1,NL)
C
  180 FORMAT(20A4,/,20A4)
  190 FORMAT(1X,30A4,/,10A4,////)
  200 FORMAT(40I2)
  210 FORMAT(4I3,2G5.0,G10.0,/,(I5,4G10.0))
  220 FORMAT(8G10.2)
  230 FORMAT(1X,'# ROW (J)',5X,'= ',I5,/,1X,'# COLUMN (I)',2X,'= ',I5,/,
```

```
     *1X,'# AQUIFER (K)',1X,'= ',I5,/,                                  MN002430
     *1X,'# PMP PERIOD',2X,'= ',I5,/,1X,'STARTING PER',2X,'= '          MN002440
     *,I5,/,1X,'INITIAL DELT',2X,'= '                                   MN002450
     *,F7.2,3X,'HRS',/,1X,'EPSILON E-SUM',' = ',F7.4,3X,'FT',/1X,'INITIAMN002460
     *L TIME',2X,'= ',F7.1,'   HR',/,1X,'STARTING DATE = ', A8,///)     MN002470
  240 FORMAT(////,'      GRID SIZE',//,5X,'MULTIPLICATION FACTOR  =',F10.MN002480
     *1,/,'    DELX :',20F6.0,/,(10X,20F6.0))                           MN002490
  250 FORMAT(/,'    DELY :',20F6.0,/,(10X,20F6.0))                      MN002500
  260 FORMAT(///,1X,'CONFINING BED DATA',//)                            MN002510
  270 FORMAT(/,9X,'CONDUCTIVITY',6X,'SPEC. STORAGE',10X,'THICKNESS',/)  MN002520
  280 FORMAT(/,3E20.7)                                                  MN002530
  290 FORMAT(///,1X,'AQUIFER DATA',//)                                  MN002540
  300 FORMAT(20G4.0)                                                    MN002550
  310 FORMAT(4(1X,E19.6))                                               MN002560
  320 FORMAT(8G10.0)                                                    MN002570
  330 FORMAT(/,I6,E20.7)                                                MN002580
  340 FORMAT(I2,78I1)                                                   MN002590
      DO 350 I=1,NC                                                     MN002600
      X(I)=X(I)*FC                                                      MN002610
  350 CONTINUE                                                          MN002620
      DO 360 J=1,NR                                                     MN002630
      Y(J)=Y(J)*FC                                                      MN002640
  360 CONTINUE                                                          MN002650
C                                                                       MN002660
      NLM1=NL-1                                                         MN002670
      NRM1=NR-1                                                         MN002680
      NCM1=NC-1                                                         MN002690
      DO 370 K=1,NL                                                     MN002700
  370 NW(K)=0                                                           MN002710
C                                                                       MN002720
      DO 380 I=1,NC                                                     MN002730
      DO 380 J=1,NR                                                     MN002740
  380 ARA(I,J)=X(I)*Y(J)                                                MN002750
      DO 390 K=1,NL                                                     MN002760
      DO 390 J=1,NR                                                     MN002770
      DO 390 I=1,NC                                                     MN002780
      SF1(I,J,K)=SC(K)*ARA(I,J)                                         MN002790
      R(I,J,K)=RCM*ARA(I,J)                                             MN002800
      H(I,J,K)=HI(I,J,K)                                                MN002810
      RADIUS(I,J,K)=0.                                                  MN002820
      Q(I,J,K)=0.                                                       MN002830
      QL(I,J,K)=0.                                                      MN002840
      QL1(I,J,K)=0.                                                     MN002850
      QL2(I,J,K)=0.                                                     MN002860
      SF2(I,J,K)=SF1(I,J,K)*2.                                          MN002870
      QRE(I,J,K)=0.                                                     MN002880
  390 CONTINUE                                                          MN002890
C                                                                       MN002900
```

```
C     BOUNDARY CONDITIONS                                               MN002910
C                                                                       MN002920
      DO 400 K=1,NL                                                     MN002930
      DO 400 I=1,NC                                                     MN002940
      DO 400 J=1,NR                                                     MN002950
      IF(SF1(I,J,K).LT.0.) SF1(I,J,K)=1.E40                             MN002960
      SF2(I,J,K)=2.*SF1(I,J,K)                                          MN002970
  400 CONTINUE                                                          MN002980
      IF(IREP.EQ.1) GO TO 420                                           MN002990
      DO 410 K=1,NL                                                     MN003000
      DO 410 J=1,NR                                                     MN003010
      DO 410 I=1,NC                                                     MN003020
  410 HO(I,J,K)=H(I,J,K)                                                MN003030
      GO TO 450                                                         MN003040
  420 CONTINUE                                                          MN003050
      DO 430 K=1,NL                                                     MN003060
      DO 430 J=1,NR                                                     MN003070
  430 READ(5,470) (HO(I,J,K),I=1,NC)                                    MN003080
      DO 440 K=1,NL                                                     MN003090
      DO 440 J=1,NR                                                     MN003100
  440 READ(5,470) (H(I,J,K),I=1,NC)                                     MN003110
  450 CONTINUE                                                          MN003120
      DO 460 K=1,NL                                                     MN003130
      DO 460 J=1,NR                                                     MN003140
      DO 460 I=1,NC                                                     MN003150
      HF(I,J,K)=H(I,J,K)                                                MN003160
  460 HC(I,J,K)=H(I,J,K)                                                MN003170
  470 FORMAT(1X,13F6.1)                                                 MN003180
C                                                                       MN003190
C     A  AND  C  COEFFECIENTS                                           MN003200
C                                                                       MN003210
      DO 490 K=1,NL                                                     MN003220
      DO 490 J=1,NR                                                     MN003230
      DO 490 I=1,NCM1                                                   MN003240
      DENOMI=TS(I,J,K)*X(I+1)+TS(I+1,J,K)*X(I)                          MN003250
      IF(DENOMI.EQ.0.) GO TO 480                                        MN003260
      CX(I,J,K)=2.*TS(I,J,K)*TS(I+1,J,K)/(DENOMI*X(I))*ARA(I,J)*(-1.)   MN003270
      GO TO 490                                                         MN003280
  480 CX(I,J,K)=TS(I+1,J,K)*(-1.)                                       MN003290
  490 CONTINUE                                                          MN003300
      DO 500 K=1,NL                                                     MN003310
      DO 500 J=1,NR                                                     MN003320
  500 CX(NC,J,K)=0.                                                     MN003330
      DO 510 K=1,NL                                                     MN003340
      DO 510 J=1,NR                                                     MN003350
      DO 510 I=2,NC                                                     MN003360
  510 AX(I,J,K)=CX(I-1,J,K)                                             MN003370
      DO 520 K=1,NL                                                     MN003380
```

```
      DO 520 J=1,NR                                                     MN003390
  520 AX(1,J,K)=0.                                                      MN003400
      DO 540 K=1,NL                                                     MN003410
      DO 540 I=1,NC                                                     MN003420
      DO 540 J=1,NRM1                                                   MN003430
      DENOMJ=TS(I,J,K)*Y(J+1)+TS(I,J+1,K)*Y(J)                          MN003440
      IF(DENOMJ.EQ.0.) GO TO 530                                        MN003450
      CY(I,J,K)=2.*TS(I,J,K)*TS(I,J+1,K)/(DENOMJ*Y(J))*ARA(I,J)*(-1.)   MN003460
      GO TO 540                                                         MN003470
  530 CY(I,J,K)=TS(I,J+1,K)*(-1.)                                       MN003480
  540 CONTINUE                                                          MN003490
      DO 550 K=1,NL                                                     MN003500
      DO 550 I=1,NC                                                     MN003510
  550 CY(I,NR,K)=0.                                                     MN003520
      DO 560 K=1,NL                                                     MN003530
      DO 560 I=1,NC                                                     MN003540
      DO 560 J=2,NR                                                     MN003550
  560 AY(I,J,K)=CY(I,J-1,K)                                             MN003560
      DO 570 K=1,NL                                                     MN003570
      DO 570 I=1,NC                                                     MN003580
  570 AY(I,1,K)=0.                                                      MN003590
C                                                                       MN003600
      IF(IWRT.EQ.0) GO TO 600                                           MN003610
      WRITE(6,610)                                                      MN003620
      DO 580 K=1,NL                                                     MN003630
      WRITE(6,640) K                                                    MN003640
      DO 580 J=1,NR                                                     MN003650
  580 WRITE(6,630) J,(TS(I,J,K),I=1,NC)                                 MN003660
      WRITE(6,620)                                                      MN003670
      DO 590 K=1,NL                                                     MN003680
      WRITE(6,640) K                                                    MN003690
      DO 590 J=1,NR                                                     MN003700
  590 WRITE(6,630) J,(H(I,J,K),I=1,NC)                                  MN003710
  600 CONTINUE                                                          MN003720
C                                                                       MN003730
  610 FORMAT(///,1X,'TRANSMISSIVITY MATRIX',//)                         MN003740
  620 FORMAT(///,1X,'HEAD MATRIX',///)                                  MN003750
  630 FORMAT(1X,I3,1X,20F6.1,/,(5X,20F6.1))                             MN003760
  640 FORMAT(//,1X,'AQUIFER ',I2,//)                                    MN003770
C                                                                       MN003780
C     TIME PERIOD LOOP                                                  MN003790
C                                                                       MN003800
  650 TIME=0.                                                           MN003810
C                                                                       MN003820
  660 FORMAT(F5.2)                                                      MN003830
      DO 1580 IPER=1,NPER                                               MN003840
      READ(5,320) KP,KPM1,NWEL,TMAX,NUMT,CDLT,DELTA                     MN003850
      DT=DELTA                                                          MN003860
```

```
      TM=0.                                                             MN003870
      DO 670 I=1,NUMT                                                   MN003880
      DT=CDLT*DT                                                        MN003890
      TM=TM+DT                                                          MN003900
      IF(TM.GE.TMAX) GO TO 680                                          MN003910
  670 CONTINUE                                                          MN003920
      GO TO 690                                                         MN003930
  680 DELTA=TMAX/TM*DELTA                                               MN003940
      NUMT=I                                                            MN003950
  690 IKP=KP+ICSPR                                                      MN003960
      WRITE(6,730) IKP,TMAX,NUMT,DELTA,CDLT                             MN003970
      WRITE(6,740) NWEL                                                 MN003980
      ICNWEL=0                                                          MN003990
      IF(NWEL.EQ.0) GO TO 720                                           MN004000
      KW=0                                                              MN004010
C     READ IN PUMPING SCHEDULE                                          MN004020
      DO 710 II=1,NWEL                                                  MN004030
      READ(5,320) I,J,K,Q(I,J,K),RADIUS(I,J,K),NW(K)                    MN004040
      IF(RADIUS(I,J,K).EQ.0.) GO TO 700                                 MN004050
      NWR(II,1)=I                                                       MN004060
      NWR(II,2)=J                                                       MN004070
      NWR(II,3)=K                                                       MN004080
      Q(I,J,K)=Q(I,J,K)*5570.41                                         MN004090
  700 CONTINUE                                                          MN004100
  710 CONTINUE                                                          MN004110
  720 CONTINUE                                                          MN004120
C                                                                       MN004130
  730 FORMAT('-',50X,'PUMPING PERIOD NO.',I4,':',F10.2,' HRS '/51X,38( 'MN004140
     *-')//53X,'NUMBER OF TIME STEPS=',I6//59X,'DELT IN  HRS  =',F10.3//MN004150
     *53X,'MULTIPLIER FOR DELT =',F10.3)                                MN004160
  740 FORMAT('-',63X,I4,' WELLS'/65X,9('-')//)                          MN004170
  750 FORMAT(41X,3I10,2F13.2)                                           MN004180
C                                                                       MN004190
C     TIME STEP LOOP                                                    MN004200
C                                                                       MN004210
      DTO=DELTA                                                         MN004220
      DO 1520 ISTEP=1,NUMT                                              MN004230
      DELTA=DELTA*CDLT                                                  MN004240
      DTN=DELTA                                                         MN004250
      ATIME=ATIME+DELTA                                                 MN004260
      TIME=TIME+DELTA                                                   MN004270
C                                                                       MN004280
C     LEAKAGE TERMS CALCULATION                                         MN004290
C                                                                       MN004300
      PI2=PI*PI                                                         MN004310
      PRE=0.                                                            MN004320
C                                                                       MN004330
      DO 840  K=1,NL                                                    MN004340
```

```
      IF(SS(K).EQ.0.) GO TO 840                                         MN004350
      IF(CM(K).EQ.0.) GO TO 840                                         MN004360
      TDIM=RATE(K)*ATIME/(SS(K)*CM(K)*CM(K))                            MN004370
      IF(TDIM.GT.10.) GO TO 820                                         MN004380
      DO 810  I=1,NC                                                    MN004390
      DO 810  J=1,NR                                                    MN004400
      SUM1=0.                                                           MN004410
      SUM2=0.                                                           MN004420
      DO 780  N=1,200                                                   MN004430
      SUM11=SUM1                                                        MN004440
      SUM21=SUM2                                                        MN004450
      AN=PI2*N*N*TDIM                                                   MN004460
      PIN=PI*N                                                          MN004470
      IF(AN.GT.TOL) AN=TOL                                              MN004480
      E=1./(EXP(AN))                                                    MN004490
      IF(E.LT.0.000001) GO TO 760                                       MN004500
      ARG1=(COS(PIN))*E                                                 MN004510
      ARG2=E                                                            MN004520
      GO TO 770                                                         MN004530
  760 ARG1=0.                                                           MN004540
      ARG2=0.                                                           MN004550
  770 SUM1=SUM1+ARG1                                                    MN004560
      SUM2=SUM2+ARG2                                                    MN004570
      IF(SUM11.EQ.SUM1.AND.SUM21.EQ.SUM2) GO TO 790                     MN004580
  780 CONTINUE                                                          MN004590
  790 CONTINUE                                                          MN004600
  800 Q1=RATE(K)/CM(K)                                                  MN004610
      QL1(I,J,K)=2.*Q1*SUM1*ARA(I,J)                                    MN004620
      QL2(I,J,K)=2.*Q1*SUM2*ARA(I,J)                                    MN004630
      PRE=RATE(K)/CM(K)                                                 MN004640
  810 CONTINUE                                                          MN004650
      GO TO 840                                                         MN004660
  820 CONTINUE                                                          MN004670
C 212 WRITE(6,8) TDIM,ATIME                                             MN004680
  830 FORMAT(/,1X,'***** TDIM =',E20.7,'AND ELAPSED TIME =',F20.1,'IN HRMN004690
     *S')                                                               MN004700
  840 CONTINUE                                                          MN004710
  850 CONTINUE                                                          MN004720
C                                                                       MN004730
C                                                                       MN004740
C     B  AND  D  COEFFICIENTS                                           MN004750
C                                                                       MN004760
      DO 860 K=1,NLM1                                                   MN004770
      DO 860 I=1,NC                                                     MN004780
      DO 860 J=1,NR                                                     MN004790
      BX(I,J,K)=SF1(I,J,K)/DELTA-(AX(I,J,K)+CX(I,J,K)+AY(I,J,K)+CY(I,J,KMN004800
     *))+R(I,J,K)+R(I,J,K+1)+QL2(I,J,K)+QL2(I,J,K+1)                    MN004810
  860 CONTINUE                                                          MN004820
```

```
      DO 870 I=1,NC                                                     MN004830
      DO 870 J=1,NR                                                     MN004840
      BX(I,J,NL)=SF1(I,J,NL)/DELTA+R(I,J,NL)+QL2(I,J,NL)                MN004850
     *-(AX(I,J,NL)+CX(I,J,NL)+AY(I,J,NL)+CY(I,J,NL))                    MN004860
  870 CONTINUE                                                          MN004870
      RTM=DTO/DTN                                                       MN004880
      DO 890 K=1,NL                                                     MN004890
      DO 890 J=1,NR                                                     MN004900
      DO 890 I=1,NC                                                     MN004910
      HOKM1=HI(I,J,K-1)                                                 MN004920
      IF(K.EQ.1) HOKM1=0.                                               MN004930
      DD=HO(I,J,K)*SF1(I,J,K)/DELTA-Q(I,J,K)+QRE(I,J,K)                 MN004940
     *+QL2(I,J,K)*HI(I,J,K)-QL1(I,J,K)*HOKM1                            MN004950
      IF(K.EQ.NL) GO TO 880                                             MN004960
      DD=DD+QL2(I,J,K+1)*HI(I,J,K)-QL1(I,J,K+1)*HI(I,J,K+1)             MN004970
  880 D(I,J,K)=DD                                                       MN004980
      DH=0.                                                             MN004990
      HO(I,J,K)=H(I,J,K)                                                MN005000
      HF(I,J,K)=HC(I,J,K)                                               MN005010
  890 H(I,J,K)=H(I,J,K)-RTM*DH                                          MN005020
      DTO=DELTA                                                         MN005030
C                                                                       MN005040
C     ITERATION LOOP                                                    MN005050
C                                                                       MN005060
      ITER=0                                                            MN005070
  900 E=0.                                                              MN005080
      EMAX=0.                                                           MN005090
      ITER=ITER+1                                                       MN005100
C                                                                       MN005110
C     ALTERNATING DIRECTION PROCEDURES                                  MN005120
C                                                                       MN005130
      DO 960 K=1,NL                                                     MN005140
      DO 960 I=1,NC                                                     MN005150
      DO 940 J=1,NR                                                     MN005160
      IF(TS(I,J,K).EQ.0.) GO TO 940                                     MN005170
      HKM1=H(I,J,K-1)                                                   MN005180
      IF(K.EQ.1) HKM1=0.                                                MN005190
      DD=D(I,J,K)+(R(I,J,K)+QL1(I,J,K))*HKM1                            MN005200
      IF(K.EQ.NL) GO TO 910                                             MN005210
      DD=DD+(R(I,J,K+1)+QL1(I,J,K+1))*H(I,J,K+1)                        MN005220
  910 IF(I.EQ.1) GO TO 920                                              MN005230
      HAX=H(I-1,J,K)*AX(I,J,K)                                          MN005240
      DD=DD-HAX                                                         MN005250
  920 IF(I.EQ.NC) GO TO 930                                             MN005260
      HCX=H(I+1,J,K)*CX(I,J,K)                                          MN005270
      DD=DD-HCX                                                         MN005280
  930 W=BX(I,J,K)-AY(I,J,K)*B(J-1,K)                                    MN005290
      B(J,K)=CY(I,J,K)/W                                                MN005300
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      G(J,K)=(DD-AY(I,J,K)*G(J-1,K))/W                                  MN005310
  940 CONTINUE                                                          MN005320
      HA=G(NR,K)                                                        MN005330
      IF(TS(I,NR,K).EQ.0.) HA=H(I,NR,K)                                 MN005340
      H(I,NR,K)=HA                                                      MN005350
      N=NR-1                                                            MN005360
  950 HA=G(N,K)-B(N,K)*H(I,N+1,K)                                       MN005370
      IF(TS(I,N,K).EQ.0.) HA=H(I,N,K)                                   MN005380
      ER=ABS(HA-H(I,N,K))                                               MN005390
      EMAX=AMAX1(ER,EMAX)                                               MN005400
      E=E+ER                                                            MN005410
      H(I,N,K)=HA                                                       MN005420
      N=N-1                                                             MN005430
      IF(N.GT.0) GO TO 950                                              MN005440
  960 CONTINUE                                                          MN005450
      DO 1020 K=1,NL                                                    MN005460
      DO 1020 J=1,NR                                                    MN005470
      DO 1000 I=1,NC                                                    MN005480
      IF(TS(I,J,K).EQ.0.) GO TO 1000                                    MN005490
      HKM1=H(I,J,K-1)                                                   MN005500
      IF(K.EQ.1) HKM1=0.                                                MN005510
      DD=D(I,J,K)+(R(I,J,K)+QL1(I,J,K))*HKM1                            MN005520
      IF(K.EQ.NL) GO TO 970                                             MN005530
      DD=DD+(R(I,J,K+1)+QL1(I,J,K+1))*H(I,J,K+1)                        MN005540
  970 IF(J.EQ.1) GO TO 980                                              MN005550
      HAY=H(I,J-1,K)*AY(I,J,K)                                          MN005560
      DD=DD-HAY                                                         MN005570
  980 IF(J.EQ.NR) GO TO 990                                             MN005580
      HCY=H(I,J+1,K)*CY(I,J,K)                                          MN005590
      DD=DD-HCY                                                         MN005600
  990 W=BX(I,J,K)-AX(I,J,K)*B(I-1,K)                                    MN005610
      B(I,K)=CX(I,J,K)/W                                                MN005620
      G(I,K)=(DD-AX(I,J,K)*G(I-1,K))/W                                  MN005630
 1000 CONTINUE                                                          MN005640
      HA=G(NC,K)                                                        MN005650
      IF(TS(NC,J,K).EQ.0.) HA=H(NC,J,K)                                 MN005660
      H(NC,J,K)=HA                                                      MN005670
      N=NC-1                                                            MN005680
 1010 HA=G(N,K)-B(N,K)*H(N+1,J,K)                                       MN005690
      IF(TS(N,J,K).EQ.0.) HA=H(N,J,K)                                   MN005700
      ER=ABS(H(N,J,K)-HA)                                               MN005710
      EMAX=AMAX1(ER,EMAX)                                               MN005720
      E=E+ER                                                            MN005730
      H(N,J,K)=HA                                                       MN005740
      N=N-1                                                             MN005750
      IF(N.GT.0) GO TO 1010                                             MN005760
 1020 CONTINUE                                                          MN005770
      IF(IWIT.EQ.0) GO TO 1030                                          MN005780
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      WRITE(6,1040) ATIME,ITER,EMAX,E                                   MN005790
 1030 CONTINUE                                                          MN005800
 1040 FORMAT('0',5X,'TIME =',F13.2,2X,'HRS',5X,'ITERATION #',I3,5X,'EMAXMN005810
     * =',E13.6,5X,'SUM EMAX =',E13.6,/)                                MN005820
      IF(ITER.EQ.IITER ) GO TO 1590                                     MN005830
      DO 1050 K=1,NL                                                    MN005840
      DO 1050 I=1,NC                                                    MN005850
      DO 1050 J=1,NR                                                    MN005860
      HC(I,J,K)= H(I,J,K)                                               MN005870
 1050 CONTINUE                                                          MN005880
      ICSS=0                                                            MN005890
      DO 1090  K=1,NL                                                   MN005900
      ES=0.                                                             MN005910
      DO 1060  I=1,NC                                                   MN005920
      DO 1060  J=1,NR                                                   MN005930
      ESME=ABS(HC(I,J,K)-HF(I,J,K))                                     MN005940
      ES  =AMAX1(ES,ESME)                                               MN005950
      DDNN(I,J,K)=HF(I,J,K)-HC(I,J,K)                                   MN005960
 1060 DDN(I,J,K)=HI(I,J,K)- H(I,J,K)                                    MN005970
      IF(ES.LE.ERROR) ICSS=ICSS+1                                       MN005980
C     WRITE(6  ,372) ES,K                                               MN005990
 1070 FORMAT(5X,'MAX  HF - HC = ',F10.1,5X,'AQUIFER ',I5)               MN006000
      IF(ES.LE.ERROR) WRITE(6,1080) ES,K                                MN006010
 1080 FORMAT(20X,'***** STEADY STATE FOR HEAD DIFF OF ',E13.6,'*****',  MN006020
     *5X,'LAYER ',I3)                                                   MN006030
 1090 CONTINUE                                                          MN006040
 1100 CONTINUE                                                          MN006050
      IF(ICSS.EQ.NL.AND.ISS.EQ.1) NUMT=ISTEP                            MN006060
C                                                                       MN006070
C     CONVERGENCE TEST                                                  MN006080
C                                                                       MN006090
      IF(EMAX.LE.ERROR) GO TO 1110                                      MN006100
      IF(E.GT.ERROR) GO TO 900                                          MN006110
 1110 CONTINUE                                                          MN006120
      IF(ISTEP.NE.NUMT) GO TO 1130                                      MN006130
      WRITE(6,1040) ATIME,ITER,EMAX,E                                   MN006140
      WRITE(6,1120) ISTEP,DELTA                                         MN006150
 1120 FORMAT(/,5X,'TIME STEP #',I3,5X,'DELTA =',F8.2,'DY')              MN006160
 1130 CONTINUE                                                          MN006170
C                                                                       MN006180
C     PRINT OUTPUT                                                      MN006190
C                                                                       MN006200
 1140 CONTINUE                                                          MN006210
      DO 1510 K=1,NL                                                    MN006220
      IF(ISTEP.NE.NUMT) GO TO 1280                                      MN006230
 1150 CONTINUE                                                          MN006240
      WRITE(6,1160) K                                                   MN006250
 1160 FORMAT('0AQUIFER ',I2,/)                                          MN006260
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      IF(IHDN.EQ.0) GO TO 1200                                          MN006270
      WRITE(6,1170)                                                     MN006280
 1170 FORMAT('0',20X,'HEAD MATRIX')                                     MN006290
      DO 1180 J=1,NR                                                    MN006300
 1180 WRITE(6,1190) J,(HC(I,J,K),I=1,NC)                                MN006310
 1190 FORMAT(/,I5,5X,20F6.1)                                            MN006320
 1200 CONTINUE                                                          MN006330
      IF(IDDN.EQ.0) GO TO 1230                                          MN006340
      WRITE(6,1210)                                                     MN006350
 1210 FORMAT('0',20X,'DRAW DOWN')                                       MN006360
      DO 1220 J=1,NR                                                    MN006370
 1220 WRITE(6,1190) J,(DDN(I,J,K),I=1,NC)                               MN006380
 1230 CONTINUE                                                          MN006390
      IF(NW(K).EQ.0) GO TO 1270                                         MN006400
      WRITE(6,1240)                                                     MN006410
 1240 FORMAT('-',50X,'HEAD AND DRAWDOWN IN PUMPING WELLS',/,51X,34('-'),MN006420
     *//,48X,'I    J    K     Q IN MGD     HEAD    DRAWDOWN  AREAL DDN  MN006430
     *    AREAL HEAD')                                                  MN006440
      DO 1260 KW=1,  NWEL                                               MN006450
      IF(NWR(KW,3).NE.K) GO TO 1260                                     MN006460
      I=NWR(KW,1)                                                       MN006470
      J=NWR(KW,2)                                                       MN006480
      KC=NWR(KW,3)                                                      MN006490
      IF(RADIUS(I,J,KC).EQ.0) GO TO 1260                                MN006500
      RE=SQRT(ARA(I,J)/PI)                                              MN006510
      HW=HC(I,J,KC)-Q(I,J,KC)*(ALOG(RE/RADIUS(I,J,KC)))/(2.*PI *TS(I,J, MN006520
     *KC))                                                              MN006530
      DRAW=HI(I,J,K)-HW                                                 MN006540
      DRAWA=HI(I,J,KC)-HC(I,J,KC)                                       MN006550
      WHEAD=HC(I,J,KC)                                                  MN006560
      QMGD=Q(I,J,KC)/5570.41                                            MN006570
      WRITE(6,1250) I,J,KC,QMGD,HW,DRAW,DRAWA,WHEAD                     MN006580
 1250 FORMAT(' ',43X,3I5,5F11.2)                                        MN006590
 1260 CONTINUE                                                          MN006600
 1270 CONTINUE                                                          MN006610
 1280 CONTINUE                                                          MN006620
C                                                                       MN006630
C     MASS BALANCE CALCULATION                                          MN006640
C                                                                       MN006650
      PUMP=0.                                                           MN006660
      STOR=0.                                                           MN006670
      FLUXS=0.                                                          MN006680
      CHD1=0.                                                           MN006690
      CHD2=0.                                                           MN006700
      CFLUX=0.                                                          MN006710
      FLXN=0.                                                           MN006720
      FLBXN=0.                                                          MN006730
      FLBXS=0.                                                          MN006740
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      OBTR=0.                                                           MN006750
      PBTR=0.                                                           MN006760
      PUTR=0.                                                           MN006770
      OUTR=0.                                                           MN006780
C                                                                       MN006790
      HU=0.                                                             MN006800
      DO 1360 I=1,NC                                                    MN006810
      DO 1360 J=1,NR                                                    MN006820
      IF(Q(I,J,K)) 1300,1310,1290                                       MN006830
C                                                                       MN006840
 1290 PUMP=PUMP-Q(I,J,K)                                                MN006850
      GO TO 1310                                                        MN006860
C                                                                       MN006870
 1300 CFLUX=CFLUX-Q(I,J,K)                                              MN006880
 1310 CONTINUE                                                          MN006890
      IF(SF1(I,J,K).GE.BNUM1) GO TO 1320                                MN006900
C                                                                       MN006910
      STOR=STOR+SF2(I,J,K)*(HO(I,J,K)-H(I,J,K))                         MN006920
 1320 CONTINUE                                                          MN006930
C                                                                       MN006940
      IF(K.EQ.1) GO TO 1330                                             MN006950
      HUO=HI(I,J,K-1)                                                   MN006960
      HU=HC(I,J,K-1)                                                    MN006970
      GO TO 1340                                                        MN006980
 1330 HU=0.                                                             MN006990
      HUO=0.                                                            MN007000
 1340 CONTINUE                                                          MN007010
      XU=HC(I,J,K)-HU                                                   MN007020
      XUO1=HUO-HU                                                       MN007030
      XUO2=HI(I,J,K)-HC(I,J,K)                                          MN007040
      UTR=XUO1*QL1(I,J,K)-XUO2*QL2(I,J,K)                               MN007050
      UL=XU*R(I,J,K)+UTR                                                MN007060
      IF(UL.GT.0.) FLUXS=FLUXS+UL                                       MN007070
      IF(UL.LT.0.) FLXN=FLXN+UL                                         MN007080
      IF(UTR.GT.0.) PUTR=PUTR+UTR                                       MN007090
      IF(UTR.LT.0.) OUTR=OUTR+UTR                                       MN007100
      HB=HC(I,J,K+1)                                                    MN007110
      HBO=HI(I,J,K+1)                                                   MN007120
      IF(K.EQ.NL) GO TO 1350                                            MN007130
      XB=HC(I,J,K)-HB                                                   MN007140
      XBO1=HBO-HB                                                       MN007150
      XBO2=HI(I,J,K+1)-HC(I,J,K+1)                                      MN007160
      BTR=XBO1*QL1(I,J,K+1)-XBO2*QL2(I,J,K+1)                           MN007170
      BL=XB*R(I,J,K+1)+BTR                                              MN007180
      IF(BL.GT.0.) FLBXS=FLBXS+BL                                       MN007190
      IF(BL.LT.0.) FLBXN=FLBXN+BL                                       MN007200
      IF(BTR.GT.0.) PBTR=PBTR+BTR                                       MN007210
      IF(BTR.LT.0.) OBTR=OBTR+BTR                                       MN007220
```

```
 1350 CONTINUE                                                          MN007230
      CLS=FLUXS+FLBXS                                                   MN007240
      CLN=FLXN+FLBXN                                                    MN007250
      TLS=PUTR+PBTR                                                     MN007260
      TLN=OUTR+OBTR                                                     MN007270
 1360 CONTINUE                                                          MN007280
C                                                                       MN007290
      XIP=0.                                                            MN007300
      YIP=0.                                                            MN007310
      XI=0.                                                             MN007320
      YI=0.                                                             MN007330
      DO 1480 I=2,NCM1                                                  MN007340
      DO 1480 J=2,NRM1                                                  MN007350
      IF(SF1(I,J,K).LT.BNUM1) GO TO 1480                                MN007360
      IF(SF1(I-1,J,K).GE.BNUM1) GO TO 1390                              MN007370
      XI=AX(I,J,K)*(H(I-1,J,K)-H(I,J,K))                                MN007380
      IF(XI) 1370,1390,1380                                             MN007390
 1370 CHD1=CHD1+XI                                                      MN007400
      GO TO 1390                                                        MN007410
 1380 CHD2=CHD2+XI                                                      MN007420
 1390 IF(SF1(I+1,J,K).GE.BNUM1) GO TO 1420                              MN007430
      XIP=CX(I,J,K)*(H(I+1,J,K)-H(I,J,K))                               MN007440
      IF(XIP) 1400,1420,1410                                            MN007450
 1400 CHD1=CHD1+XIP                                                     MN007460
      GO TO 1420                                                        MN007470
 1410 CHD2=CHD2+XIP                                                     MN007480
 1420 IF(SF1(I,J-1,K).GE.BNUM1) GO TO 1450                              MN007490
      YI=AY(I,J,K)*(H(I,J-1,K)-H(I,J,K))                                MN007500
      IF(YI) 1430,1450,1440                                             MN007510
 1430 CHD1=CHD1+YI                                                      MN007520
      GO TO 1450                                                        MN007530
 1440 CHD2=CHD2+YI                                                      MN007540
 1450 IF(SF1(I,J+1,K).GE.BNUM1) GO TO 1480                              MN007550
      YIP=CY(I,J,K)*(H(I,J+1,K)-H(I,J,K))                               MN007560
      IF(YIP) 1460,1480,1470                                            MN007570
 1460 CHD1=CHD1+YIP                                                     MN007580
      GO TO 1480                                                        MN007590
 1470 CHD2=CHD2+YIP                                                     MN007600
 1480 CONTINUE                                                          MN007610
C                                                                       MN007620
      STORT(K)=STORT(K)+STOR                                            MN007630
      CHDT(K)=CHDT(K)-CHD1*DELTA                                        MN007640
      CHST(K)=CHST(K)+CHD2*DELTA                                        MN007650
      PUMPT(K)=PUMPT(K)-PUMP*DELTA                                      MN007660
      CLST(K)=CLST(K)+CLS*DELTA                                         MN007670
      CLNT(K)=CLNT(K)-CLN*DELTA                                         MN007680
      TLST(K)=TLST(K)+TLS*DELTA                                         MN007690
      TLNT(K)=TLNT(K)-TLN*DELTA                                         MN007700
```

```
      TOTL1(K)=STORT(K)+CHST(K)+CLST(K)                                 MN007710
      TOTL2(K)=PUMPT(K)+CHDT(K)+CLNT(K)                                 MN007720
      SUMR(K)=STOR/DELTA+CHD2+CHD1+CLS+CLN+PUMP                         MN007730
      DIFF(K)=TOTL1(K)-TOTL2(K)                                         MN007740
      PERCNT(K)=DIFF(K)/(TOTL1(K)+TOTL2(K))*200.                        MN007750
      IF(IWMB.NE.1) GO TO 1500                                          MN007760
      IF(ISTEP.NE.NUMT) GO TO 1500                                      MN007770
C                                                                       MN007780
      WRITE(6,1490) K,STORT(K),STOR,CHST(K)        ,CHD2,CLST(K),CHD1,  MN007790
     *      TOTL1(K)     ,PUMPT(K),CLS,CHDT(K)            ,CLN,CLNT(K),  MN007800
     * PUMP,TOTL2(K),SUMR(K),DIFF(K),PERCNT(K)                          MN007810
 1490 FORMAT('0',2X,'AQUIFER',I2,4X,                                    MN007820
     *                'CUMULATIVE VOLUME :',38X,'TIME STEP RATES :',//,  MN007830
     *1X,'SOURCE :',17X,'STORAGE =',F20.2,26X,'STORAGE =',F20.4,/,20X,  MN007840
     *'CONSTANT HEAD =',F20.2,19X,'CONSTANT HEAD:  ',/,19X,'            MN007850
     *    '       ,31X,'IN =',F20.4,/,19X,'TOTAL  LEAKAGE =',F20.2,30X, MN007860
     *'OUT =',F20.4,/,28X,'TOTAL  ',F20.2,25X,'LEAKAGE:'/77X, 'IN :     MN007870
     *    '       ,/,1X,'DISCHARGE :',14X,'PUMPING =',F20.2,27X,'TOTAL  =MN007880
     *',F20.4,/,20X,'CONSTANT HEAD =',F20.2,21X,'OUT :          '       MN007890
     *,/,19X,'                    '       ,27X,'TOTAL  =',F20.4,/,19X,  MN007900
     *'TOTAL  LEAKAGE =',F20.2,29X,'PUMP =',F20.4,/,28X,'TOTAL  ',F20.2,MN007910
     *28X,'TOTAL  ',F20.4,//,26X,'BALANCE  ',F20.2,/,                   MN007920
     *23X,'PERCENTAGE  ',F20.2,//)                                      MN007930
 1500 CONTINUE                                                          MN007940
 1510 CONTINUE                                                          MN007950
      IF(ICSS.EQ.NL.AND.ISS.EQ.1) GO TO 1530                            MN007960
 1520 CONTINUE                                                          MN007970
 1530 CONTINUE                                                          MN007980
      TSTORT=0.                                                         MN007990
      TCHDS=0.                                                          MN008000
      TCLST=0.                                                          MN008010
      TPUMPT=0.                                                         MN008020
      TCHDT=0.                                                          MN008030
      TCLNT=0.                                                          MN008040
      DO 1540 K=1,NL                                                    MN008050
      TSTORT=TSTORT+STORT(K)                                            MN008060
      TCHDS=TCHDS+CHST(K)                                               MN008070
      TCLST=TCLST+CLST(K)                                               MN008080
      TPUMPT=TPUMPT+PUMPT(K)                                            MN008090
      TCHDT=TCHDT+CHDT(K)                                               MN008100
      TCLNT=TCLNT+CLNT(K)                                               MN008110
 1540 CONTINUE                                                          MN008120
      SUMS=TSTORT+TCHDS+TCLST                                           MN008130
      SUMN=TCHDT+TPUMPT+TCLNT                                           MN008140
      SPN=SUMS+SUMN                                                     MN008150
      SMN=SUMS-SUMN                                                     MN008160
      DIFSN=SMN/SPN*200.                                                MN008170
C                                                                       MN008180
```

```
      E(6,1560) TSTORT,TPUMPT,TCHDS,TCHDT,TCLST,TCLNT,SUMS,SUMN,SMN,MN008190
      SN                                                            MN008200
      TINUE                                                         MN008210
1560  (MAT(//,15X,'TOTAL MASS BALANCE :',//,26X,                    MN008220
     *              'STORAGE =',F20.2,26X,'PUMPING =',F20.2,/,18X,'POS CMN008230
     *ONST. HEAD =',F20.2,18X,'NEG CONST. HEAD =',F20.2,/,22X,'POS LEAKAMN008240
     *GE =',F20.2,22X,'NEG LEAKAGE =',F20.2,//,28X,'TOTAL  ',F20.2,28X,'MN008250
     *TOTAL  ',F20.2,//,26X,'BALANCE =',F20.2,/,23X,'PERCENTAGE =',F20.2MN008260
     *,//)                                                          MN008270
1570  CONTINUE                                                      MN008280
      IF(ICSS.EQ.NL.AND.ISS.EQ.1) GO TO 1630                        MN008290
1580  CONTINUE                                                      MN008300
      IF(IWCH.NE.1) GO TO 1640                                      MN008310
      DO 1590 K=1,NL                                                MN008320
      WRITE(6,310) STORT(K),CHDT(K),CHST(K),PUMPT(K)                MN008330
      WRITE(6,310) CLST(K),CLNT(K),TLST(K),TLNT(K)                  MN008340
1590  CONTINUE                                                      MN008350
      WRITE(6,1600)                                                 MN008360
1600  FORMAT(/,1X,'*** HO(I,J,K) ***',/,4X,'-----------',/)         MN008370
      DO 1610 K=1,NL                                                MN008380
      WRITE(6,1160) K                                               MN008390
      DO 1610 J=1,NR                                                MN008400
      WRITE(6,630) J,(HO(I,J,K),I=1,NC)                             MN008410
1610  CONTINUE                                                      MN008420
      WRITE(6,1620)                                                 MN008430
1620  FORMAT(/,1X,'+++ H(I,J,K) +++',/,4X,'----------',/)           MN008440
      DO 1630 K=1,NL                                                MN008450
      WRITE(6,1160) K                                               MN008460
      DO 1630 J=1,NR                                                MN008470
      WRITE(6,630) J,(H(I,J,K),I=1,NC)                              MN008480
1630  CONTINUE                                                      MN008490
1640  CONTINUE                                                      MN008500
      IF(IPCH.NE.1) GO TO 1690                                      MN008510
      DO 1650 K=1,NL                                                MN008520
      WRITE(7,310) STORT(K),CHDT(K),CHST(K),PUMPT(K)                MN008530
      WRITE(7,310) CLST(K),CLNT(K),TLST(K),TLNT(K)                  MN008540
1650  CONTINUE                                                      MN008550
      DO 1660 K=1,NL                                                MN008560
      DO 1660 J=1,NR                                                MN008570
1660  WRITE(7,470) (HO(I,J,K),I=1,NC)                               MN008580
      DO 1670 K=1,NL                                                MN008590
      DO 1670 J=1,NR                                                MN008600
1670  WRITE(7,470) (H(I,J,K),I=1,NC)                                MN008610
       IF(MAP.EQ.0) GO TO 1680                                      MN008620
      CALL MAP                                                      MN008630
1680  CONTINUE                                                      MN008640
      IF(ITER.EQ.IITER) WRITE(6,1690) ITER                          MN008650
1690  FORMAT(/,1X,' ***  ',I5,'  ITERATIONS EXCEEDED  ***')         MN008660

      STOP                                                          MN008670
      END                                                           MN008680
```

```
      SUBROUTINE MAP                                                    MP001000
C                                                                       MP001010
      COMMON     H(35,25,4),SF1(35,25,4),X(35),Y(25),                   MP001020
     *           Q(35,25,4),NC,NR,NL,IKP                                MP001030
C                                                                       MP001040
      DIMENSION VF4(11)                                                 MP001050
      DIMENSION XLABEL(3),TTLE(5),SYM(28),PRNT(122),BLANK(60),DIGIT(122)MP001060
     *          ,VF1(6),VF2(6),VF3(7),NA(4),XN(100),YN(13),YLABEL(3)    MP001070
C                                                                       MP001080
      REAL *4 KPRM                                                      MP001090
      REAL *8XLABEL,YLABEL,TTLE                                         MP001100
      INTEGER OUT                                                       MP001110
      DATA TTLE/'ALPHAMER','IC CONTO','URS OF H','EAD'/                 MP001120
      DATA SYM/1H ,1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9,1H ,1HA,1HB,1HC,1MP001130
     *HD,1HE,1HF,1HG,1HH,1HI,1H ,1H*,1H|,1H-,1H+,1H0,1HR,1HW/           MP001140
      DATA PRNT/122*' '/,N1,N2,N3,XN1/6,10,133,.0833333333D0/,BLANK/60*'MP001150
     * '/,NA(4)/1000/                                                   MP001160
      DATA DIGIT/'1','2','3','4','5','6','7','8','9','10','11','12','13'MP001170
     *,'14','15','16','17','18','19','20','21','22','23','24','25','26',MP001180
     *'27','28','29','30','31','32','33','34','35','36','37','38','39','MP001190
     *40','41','42','43','44','45','46','47','48','49','50','51','52','5MP001200
     *3','54','55','56','57','58','59','60','61','62','63','64','65','66MP001210
     *','67','68','69','70','71','72','73','74','75','76','77','78',' 79MP001220
     *','80','81','82','83','84','85','86','87','88','89','90','91','92'MP001230
     *,'93','94','95','96','97','98','99','100','101','102','103',' 104'MP001240
     *,'105','106','107','108','109','110','111','112','113','114','115'MP001250
     *,'116','117','118','119','120','121','122'/                       MP001260
      DATA VF1/'(1H ',',',',    ','A1,F','10.2',')'/                    MP001270
      DATA VF2/'(1H ',',',',    ','A1,1','X,A8',')'/                    MP001280
      DATA VF3/'(1H0',',',',    ','A1,F','3.1',','12F1','0.2)'/         MP001290
      DATA VF4/'(1H0',',',',    ','X,I2',',2X,','20F6','.1/(','    ','X,2MP001300
     *0','F6.1','))'/                                                   MP001310
      DATA XLABEL /' X DIS- ','TANCE IN','  MILES '/,YLABEL/' Y DISTA','MP001320
     *NCE IN  ','  MILES '/                                             MP001330
      DELX=5280.                                                        MP001340
      DELY=5280.                                                        MP001350
      BNUM1=.5E40                                                       MP001360
      JNO1=NC-1                                                         MP001370
      INO1=NR-1                                                         MP001380
      DINCH=2.                                                          MP001390
      SCALE=5280.                                                       MP001400
      SPACNG=5.                                                         MP001410
  100 FORMAT(20G4.0)                                                    MP001420
  110 FORMAT(//,1X,'LAYER   ',I2,//)                                    MP001430
  120 FORMAT(1X,I3,1X,20F6.1,/,5X,20F6.1)                               MP001440
      WIDTH=0.                                                          MP001450
      YDIM=0.                                                           MP001460
```

```
      DO 130 I=1,NC                                                     MP001470
  130 WIDTH=WIDTH+X(I)                                                  MP001480
      DO 140 J=1,NR                                                     MP001490
  140 YDIM=YDIM+Y(J)                                                    MP001500
      IM=MIN0(6*NR+4,124)                                               MP001510
      IM=(132-IM)/2                                                     MP001520
      VF4(3)=DIGIT(IM)                                                  MP001530
      VF4(8)=DIGIT(IM+5)                                                MP001540
  150 XSF=DINCH*SCALE                                                   MP001550
      NYD=YDIM/XSF                                                      MP001560
      IF(NYD*XSF.LE.YDIM-Y(NR)/2.) NYD=NYD+1                            MP001570
      IF (NYD.LE.12) GO TO 160                                          MP001580
      DINCH=YDIM/(12.*SCALE)                                            MP001590
      WRITE(6,170) DINCH                                                MP001600
      IF(SCALE.LT.1.0) WRITE(6,180)                                     MP001610
      GO TO 150                                                         MP001620
  160 NXD=WIDTH/XSF                                                     MP001630
  170 FORMAT(/,' SCALE SHOULD BE ',F10.2)                               MP001640
  180 FORMAT(/,' SCALE SHOULD BE GT 1.')                                MP001650
      IF(NXD*XSF.LE.WIDTH-X(NC)/2.) NXD=NXD+1                           MP001660
      N4=NXD*N1+1                                                       MP001670
      N5=NXD+1                                                          MP001680
      N6=NYD+1                                                          MP001690
      N8=N2*NYD+1                                                       MP001700
      NA(1)=N4/2-1                                                      MP001710
      NA(2)=N4/2                                                        MP001720
      NA(3)=N4/2+3                                                      MP001730
      NCC=(N3-N8-10)/2                                                  MP001740
      ND=NCC+N8                                                         MP001750
      NE=MAX0(N5,N6)                                                    MP001760
      VF1(3)=DIGIT(ND)                                                  MP001770
      VF2(3)=DIGIT(ND)                                                  MP001780
      VF3(3)=DIGIT(NCC)                                                 MP001790
      DO 210 I=1,NE                                                     MP001800
      NNX=N5-I                                                          MP001810
      NNY=I-1                                                           MP001820
      IF(NNY.GE.N6) GO TO 190                                           MP001830
      YN(I)=XSF*NNY/SCALE                                               MP001840
  190 IF(NNX.LT.0) GO TO 200                                            MP001850
      XN(I)=XSF*NNX/SCALE                                               MP001860
  200 CONTINUE                                                          MP001870
  210 CONTINUE                                                          MP001880
      DO 440 K=1,NL                                                     MP001890
      DIST=WIDTH-X(1)/2.                                                MP001900
      JJ=JN01                                                           MP001910
      JJ=NC                                                             MP001920
      LL=1                                                              MP001930
      Z=NXD*XSF                                                         MP001940
```

```
      IF(K.EQ.1) WRITE(6,220) IKP                                       MP001950
      IF(K.EQ.2) WRITE(6,230) IKP                                       MP001960
      IF(K.EQ.3) WRITE(6,240) IKP                                       MP001970
      IF(K.EQ.4) WRITE(6,250) IKP                                       MP001980
  220 FORMAT('1',5X,'PLEISTOCENE AQUIFER  ',7X,'PERIOD # ',I4)          MP001990
  230 FORMAT('1',5X,'POCOMOKE AQUIFER     ',7X,'PERIOD # ',I4)          MP002000
  240 FORMAT('1',5X,'OCEAN CITY AQUIFER   ',7X,'PERIOD # ',I4)          MP002010
  250 FORMAT('1',5X,'MANOKIN AQUIFER      ',7X,'PERIOD # ',I4)          MP002020
      WRITE(6  ,410) (TTLE(I),I=1,4)                                    MP002030
      DO 400 I=1,N4                                                     MP002040
      IF (I.EQ.1.OR.I.EQ.N4) GO TO 260                                  MP002050
      PRNT(1)=SYM(23)                                                   MP002060
      PRNT(N8)=SYM(23)                                                  MP002070
      IF ((I-1)/N1*N1.NE.I-1) GO TO 290                                 MP002080
      PRNT(1)=SYM(25)                                                   MP002090
      PRNT(N8)=SYM(25)                                                  MP002100
      GO TO 290                                                         MP002110
  260 DO 280 J=1,N8                                                     MP002120
      JM1=J-1                                                           MP002130
      IF(JM1/N2*N2.EQ.JM1) GO TO 270                                    MP002140
      PRNT(J)=SYM(24)                                                   MP002150
      GO TO 280                                                         MP002160
  270 PRNT(J)=SYM(25)                                                   MP002170
  280 CONTINUE                                                          MP002180
      GO TO 350                                                         MP002190
  290 IF (DIST.LT.0..OR.DIST.LT.Z-XN1*XSF) GO TO 350                    MP002200
      YLEN=Y(1)/2.                                                      MP002210
      DO 340 L=1,NR                                                     MP002220
      J=YLEN*N2/XSF+1.5                                                 MP002230
      KPRM=H(JJ,L,K)/SPACNG                                             MP002240
      IF(KPRM) 300,310,300                                              MP002250
  300 KPRM=ABS(KPRM)                                                    MP002260
      IF(KPRM.GT.0..AND.KPRM.LT.1.)  GO TO 320                          MP002270
      KPRM=AMOD(KPRM,20.)                                               MP002280
      N=KPRM                                                            MP002290
      PRNT(J)=SYM(N+1)                                                  MP002300
      GO TO 330                                                         MP002310
  310 PRNT(J)=SYM(26)                                                   MP002320
      GO TO 330                                                         MP002330
  320 PRNT(J)=SYM(22)                                                   MP002340
  330 IF(SF1(JJ,L,K).GT.BNUM1) PRNT(J)=SYM(27)                          MP002350
      IF(Q(JJ,L,K).NE.0.) PRNT(J)=SYM(28)                               MP002360
  340 YLEN=YLEN+(Y(L)+Y(L+1))/2.                                        MP002370
      DIST=DIST-(X(JJ)+X(JJ-1))/2.                                      MP002380
      JJ=JJ-1                                                           MP002390
  350 CONTINUE                                                          MP002400
      IF (I-NA(LL).EQ.0) GO TO 370                                      MP002410
      IF ((I-1)/N1*N1-(I-1)) 380,360,380                                MP002420
```

```
360 WRITE (6,VF1) (BLANK(J),J=1,NCC),(PRNT(J),J=1,N8),XN(1+(I-1)/6)    MP002430
    GO TO 390                                                          MP002440
370 WRITE (6,VF2) (BLANK(J),J=1,NCC),(PRNT(J),J=1,N8),XLABEL(LL)       MP002450
    LL=LL+1                                                            MP002460
    GO TO 390                                                          MP002470
380 WRITE (6,VF2) (BLANK(J),J=1,NCC),(PRNT(J),J=1,N8)                  MP002480
390 Z=Z-2.*XN1*XSF                                                     MP002490
    DO 400 J=1,N8                                                      MP002500
400 PRNT(J)=SYM(11)                                                    MP002510
    WRITE (6,VF3) (BLANK(J),J=1,NCC),(YN(I),I=1,N6)                    MP002520
    WRITE(6,420) (YLABEL(I),I=1,3)                                     MP002530
    WRITE(6,430) SPACNG                                                MP002540
410 FORMAT(//,46X,4A8,//)                                              MP002550
420 FORMAT('0',39X,6A8)                                                MP002560
430 FORMAT(//,' CONTOUR INTERVAL  =',F10.2)                            MP002570
440 CONTINUE                                                           MP002580
    RETURN                                                             MP002590
    END                                                                MP002600
```

APPENDIX IV

COMPUTER INPUT DATA-DECK SETUP

Figures 13 to 22 show the arrangement of the input data cards. Values used for the Ocean City model were punched in the cards as an example. The first two cards (fig. 13) are the title cards. A 160-character title can be accommodated. The parameter card determines the dimension of the grid, number of pumping period, size of the first time step, closure criterion and previous simulation time (in hour).

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Title card	1–80	20A4	TITLE	Title of the project
Parameter card	1–3	I3	NC	Number of columns
	4–6	I3	NR	Number of rows
	7–9	I3	NL	Number of aquifers
	10–12	I3	NPER	Number of pumping period
	13–17	G5.0	DELTA	Time step size
	18–22	G5.0	ERROR	Closure criterion
	23–33	G10.0	ATIME	Previous simulation time, 0 when starting a new simulation.

The confining beds are numbered according to the position of the aquifer below it. On top of aquifer 1 is confining bed 1, and so on. The following cards (fig. 14) assign a single default value for a parameter which is assumed to be uniform. In this model the values of aquifer storage coefficient and confining bed hydraulic properties are assumed to be uniform.

Four aquifers were used in the Ocean City model. One card is required for each aquifer and its overlying confining bed.

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Default value card	1–5	I5	K	Counting number for aquifer and its overlying confining bed
	6–15	G10.0	SC(K)	Aquifer storage coefficient
	16–25	G10.0	RATE(K)	Leakance factor K′/b′
	26–35	G10.0	SS(K)	Confining bed specific storage
	36–45	G10.0	CM(K)	Confining bed thickness

The option card (fig. 15) specifies the maximum number of iterations and selects options. Insert 1 if an option is to be performed, and 0 if it is not wanted.

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Option card	1–2	I2	IITER	Maximum number of iteration
	3	I1	IHDN	Print out of computed head
	4	I1	IDDN	Print out of computed drawdowns
	5	I1	IWRT	Print out of transmissivity arrays
	6	I1	ISS	Steady-state run
	7	I1	IREP	Continuation run
	8	I1	IPCH	Punch out of head for a continuation run
	9	I1	IMAP	Print out of map
	10	I1	IWMB	Print out of material balance
	11	I1	IWCH	Print out of head for a continuation run

The next cards (fig. 15, 16) assign values to the material balance parameters for a continuation run. For a new simulation, use blank cards.

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Material-balance parameter	2–20	E19.6	STORT(K)	Volume from storage
	22–40	E19.6	CHDT(K)	Recharge from constant head nodes
	42–60	E19.6	CHST(K)	Discharge from constant head nodes
	62–80	E19.6	PUMT(K)	Volume pumped
	2–20	E19.6	CLST(K)	Recharge from leakage
	22–40	E19.6	CLNT(K)	Discharge from leakage
	42–60	E19.6	TLNT(K)	Recharge from transient leakage
	62–80	E19.6	TLST(K)	Discharge from transient leakage

The grid spacing is specified by the next set of cards (fig. 17).

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Grid spacing	1–10	G10.0	FC	Multiplication factor for grid spacing
	1–80	G4.0	X(I)	Grid spacing in the X-direction, 20 values in each card.
	1–80	G4.0	Y(J)	Grid spacing in the Y-direction, 20 values in each card.

The next group of cards specify the transmissivity arrays (fig. 18, 19). One factor card followed by one set of value cards are needed for each aquifer. Each number on the transmissivity-value cards is multiplied by the number on the factor card as the matrix is read.

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Factor card	1–10	G10.0	FCT(K)	Multiplication factor. One card for each aquifer.
Transmissivity value card	1–80	G4.0	TS(I, J, K)	Transmissivity, 20 values for each card. Each new row started with a new card.

Head arrays for each aquifer follow the transmissivity arrays (fig. 20, 21). If initial conditions are related to drawdown rather than head, drawdown values are entered in the head arrays.

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Head	1–80	G4.0	HI(I, J, K)	Head or drawdown distribution, 20 values on each card. Each new row started with a new card.

Pumping period and well cards follow the head cards (fig. 22). One pumping period card plus one well card for each well pumped during the period are required for each pumping period. In the example shown on figure 22, no wells are pumped during the first period (KP = 1, NWEL = 0); thus no well cards are required. Four wells are pumped during pumping period number two (KP = 2, NWEL = 4); thus four well cards are required (only the first and last well cards are shown in the example).

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Pumping period	1–10	G10.0	KP	Current pumping period counting number
	11–20	G10.0	KPM1	Previous pumping period counting number
	21–30	G10.0	NWEL	Number of well
	31–40	G10.0	TMAX	Total period of pumping
	41–50	G10.0	NUMT	Estimated number of time steps
	51–60	G10.0	CDLT	Multiplication factor for the size of time step

CARD	COLUMN	FORMAT	PARAMETER	EXPLANATION
Well card	1–10	G10.0	I	X position of the well
	11–20	G10.0	J	Y position of the well
	21–30	G10.0	K	Z position of the well
	31–40	G10.0	Q(I, J, K)	Rate of withdrawal
	41–50	G10.0	RADIUS (I, J, K)	Radius of the well
	51–60	G10.0	NW(K)	Total number of wells in aquifer K

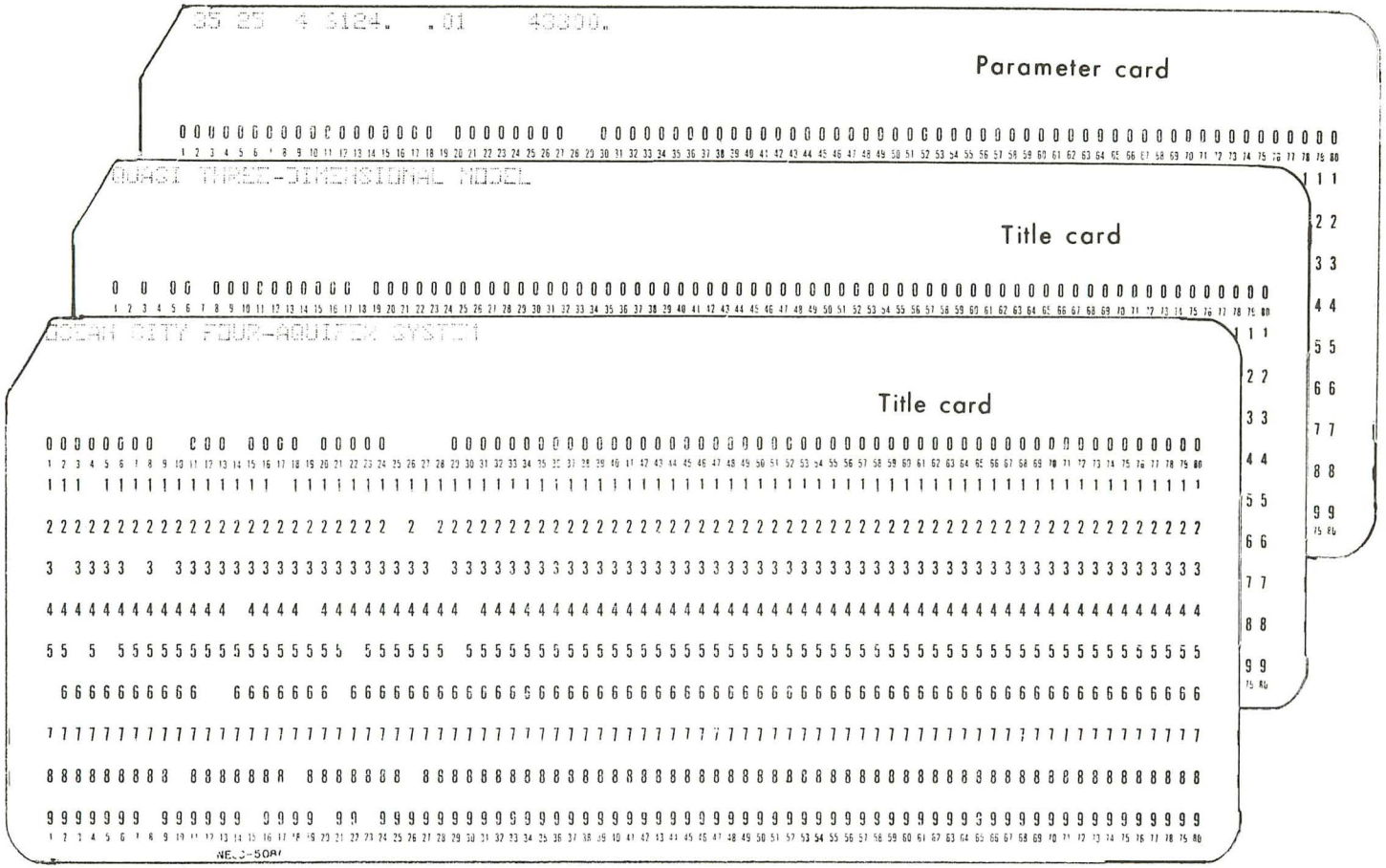

Figure 13. Data-deck setup: Title and parameter cards.

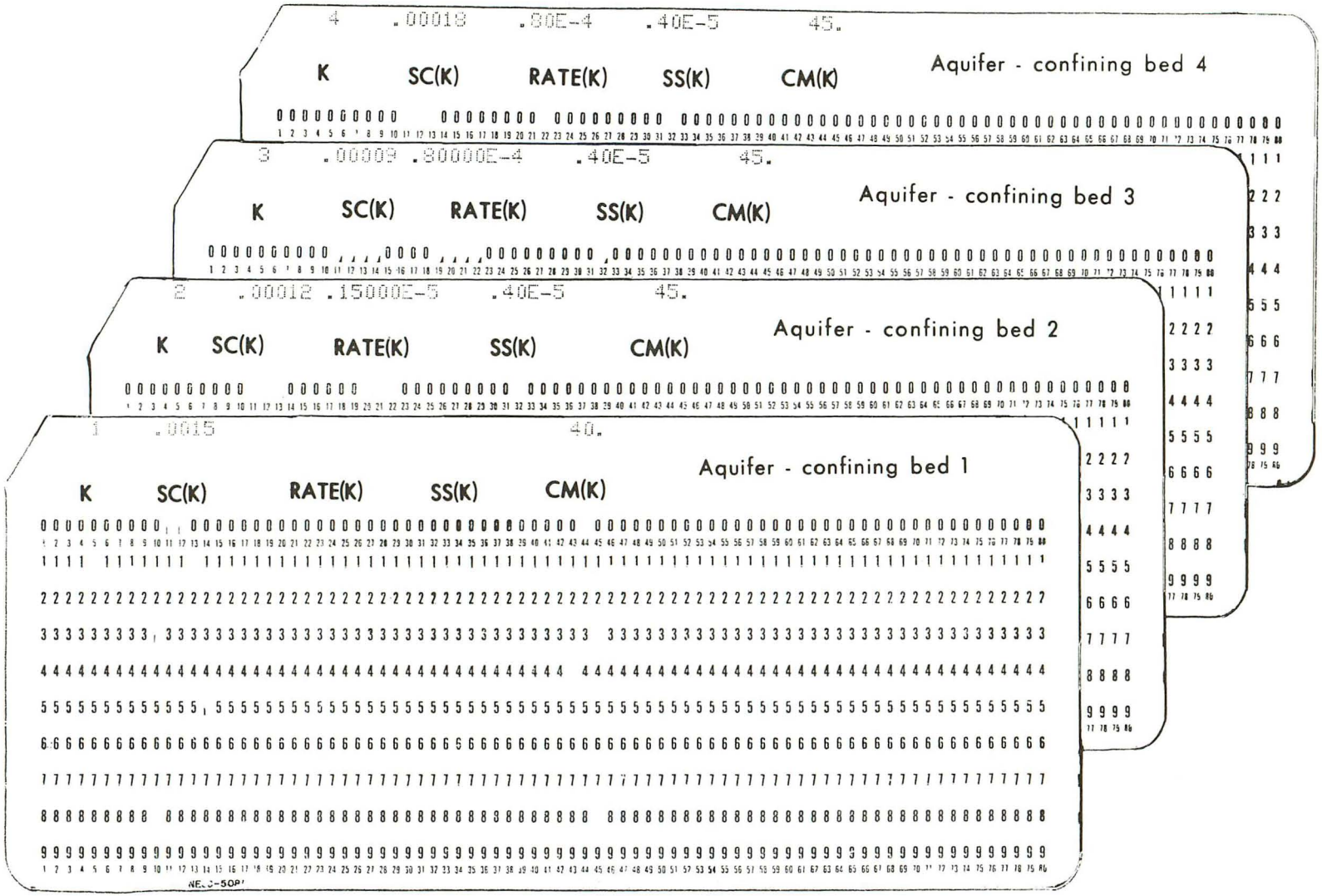

Figure 14. Data-deck setup: Aquifer and confining bed parameter default value cards.

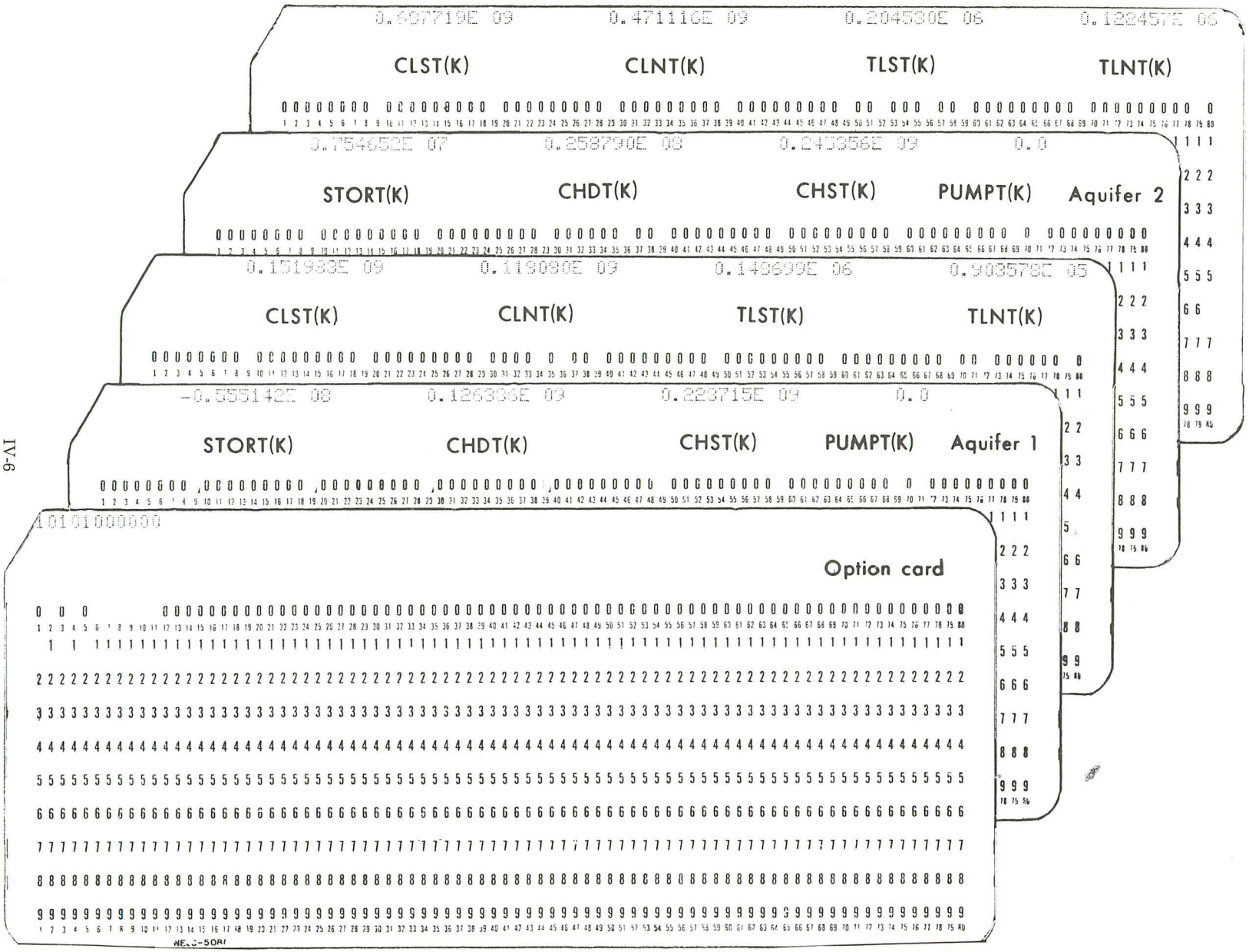

Figure 15. Data-deck setup: Options and material-balance values.

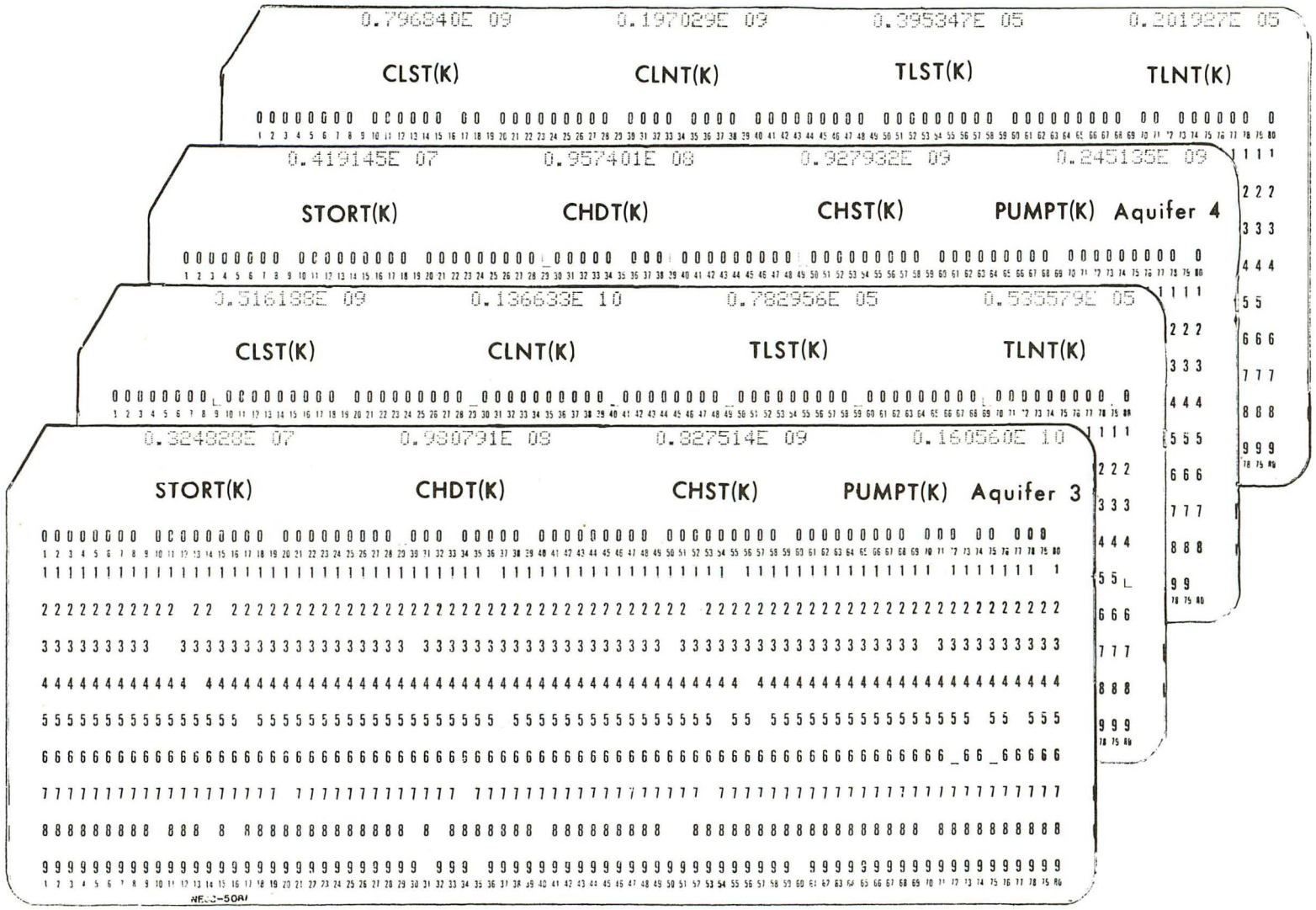

Figure 16. Data-deck setup: Material-balance values (continued).

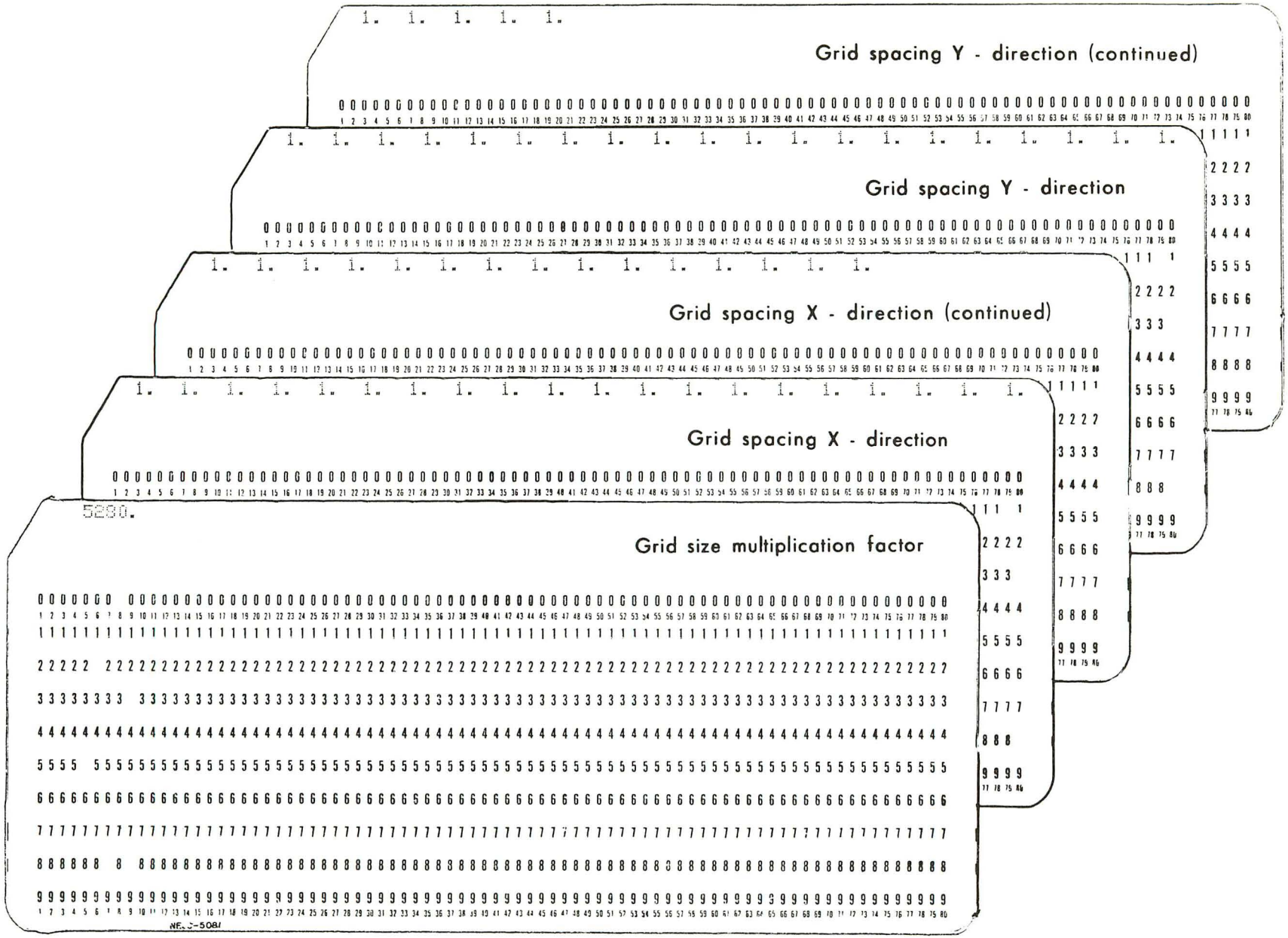

Figure 17. Data-deck setup: Grid spacing.

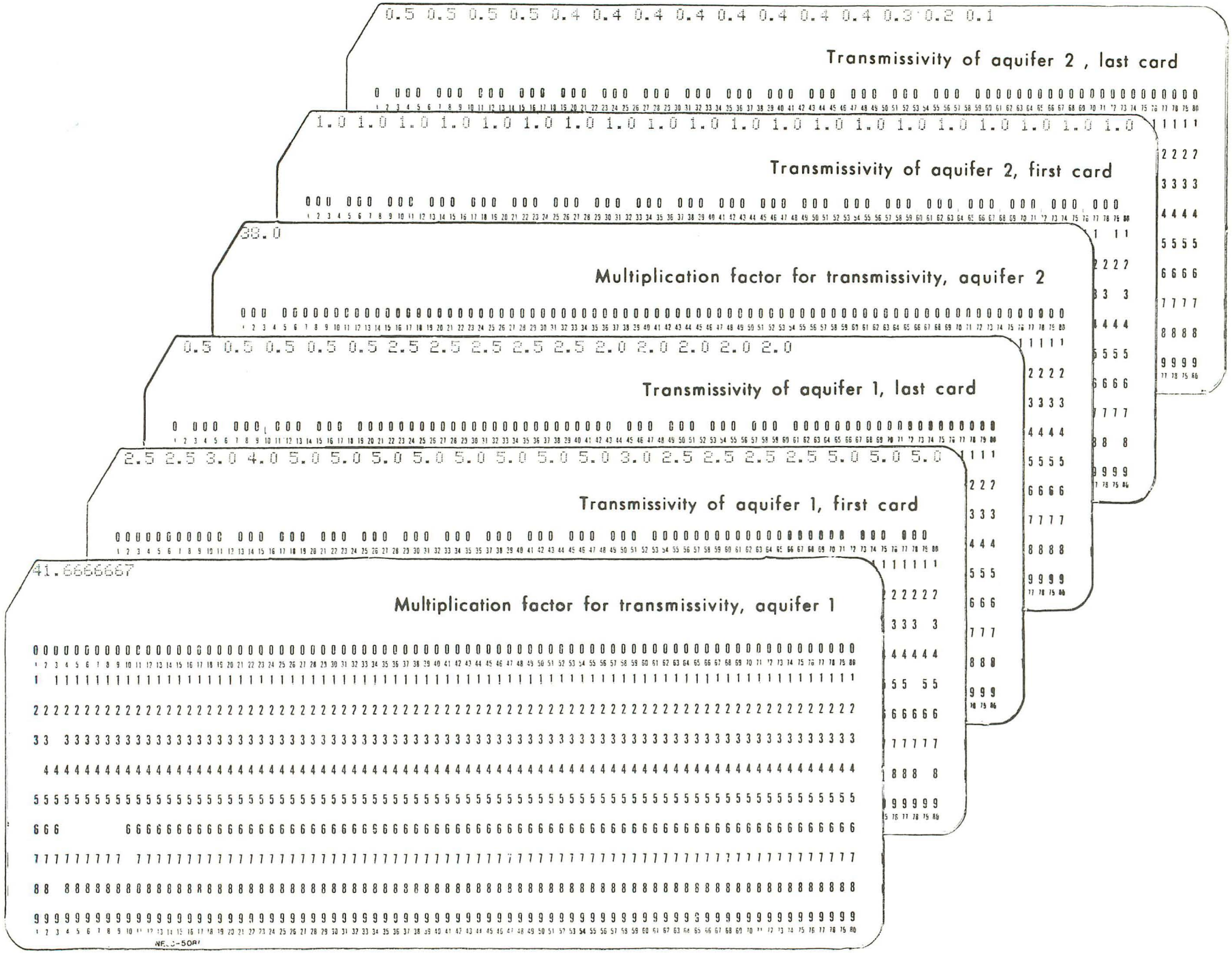

Figure 18. Data-deck setup: Transmissivity arrays.

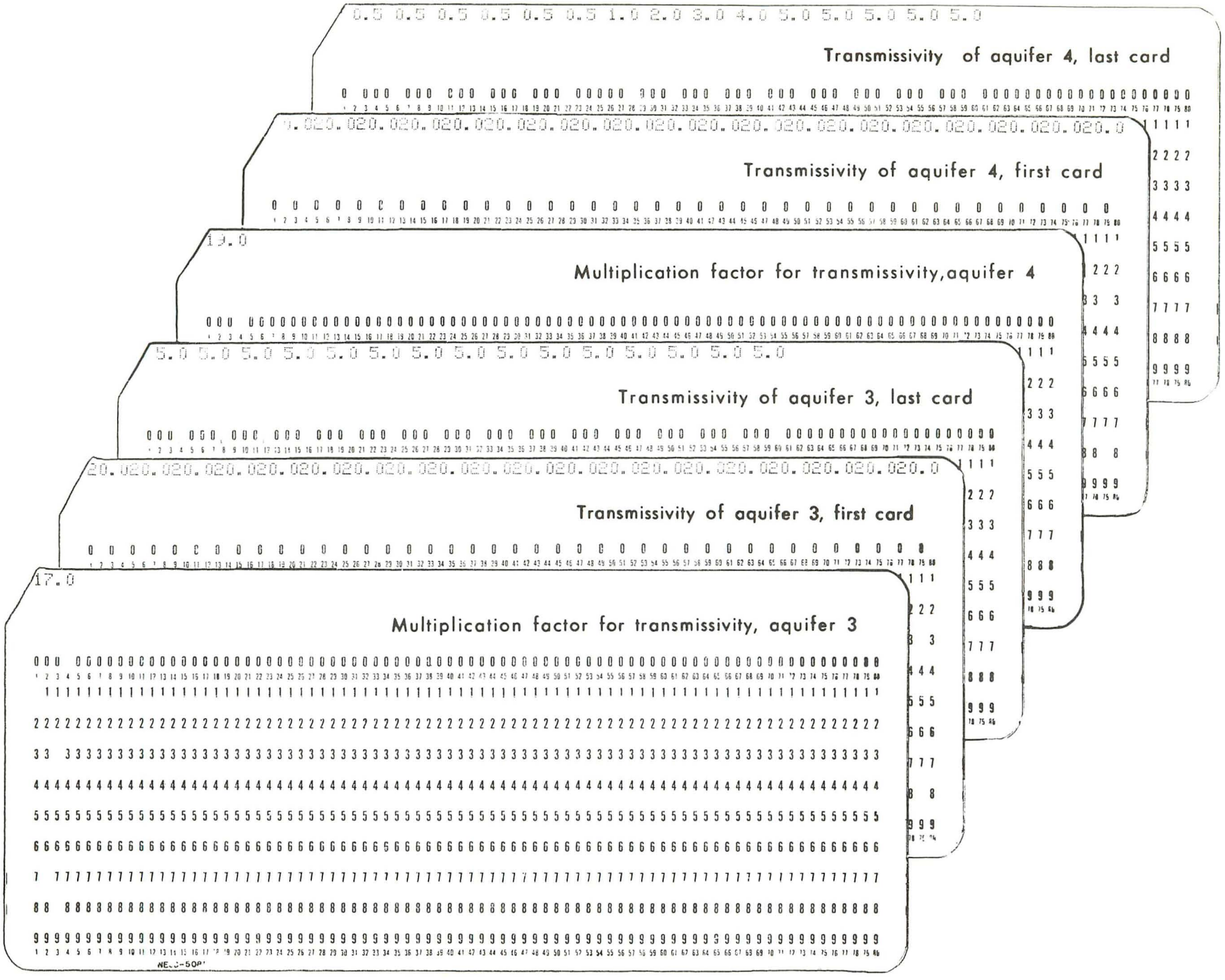

Figure 19. Data-deck setup: Transmissivity arrays (continued).

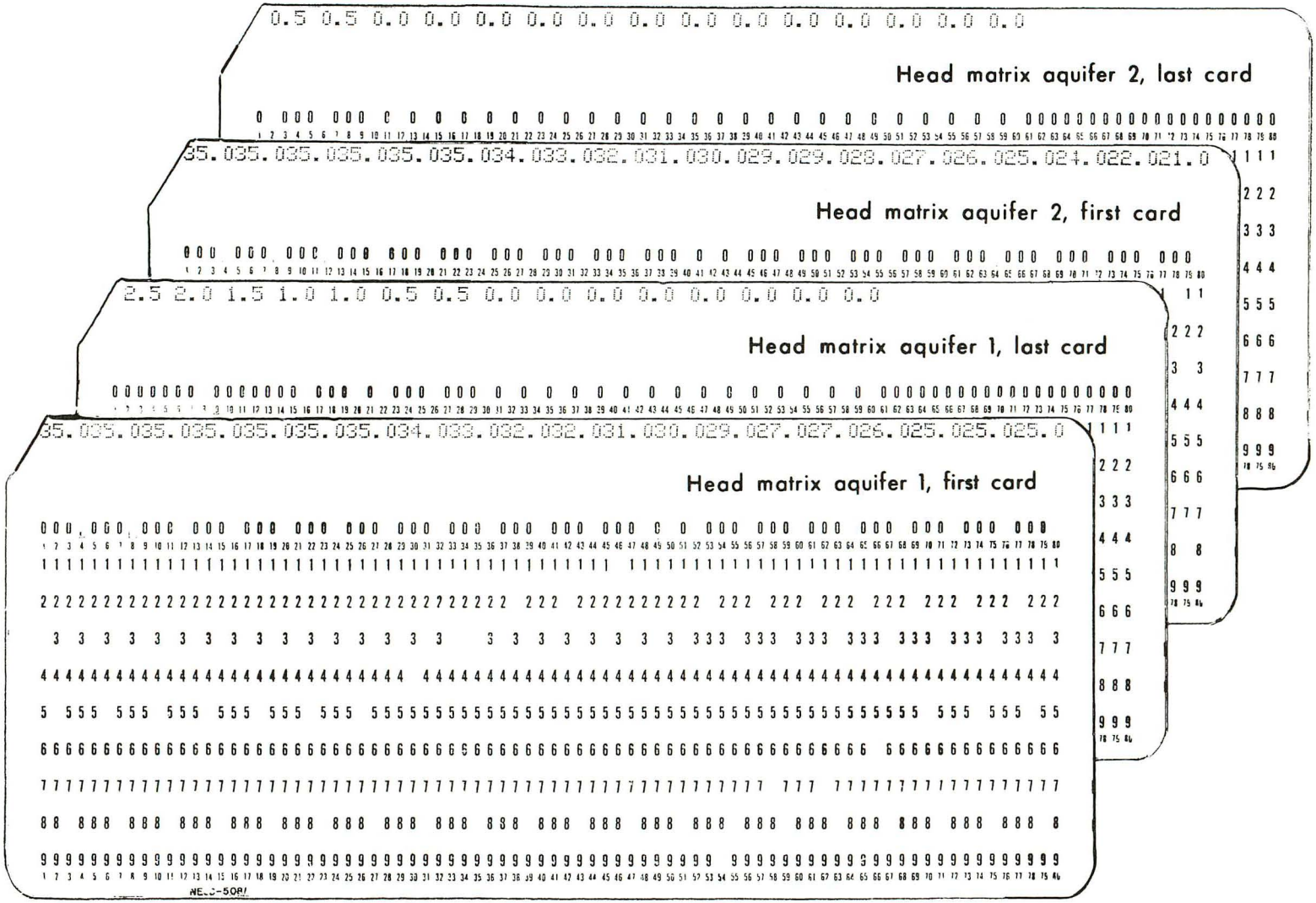

Figure 20. Data-deck setup: Head matrix.

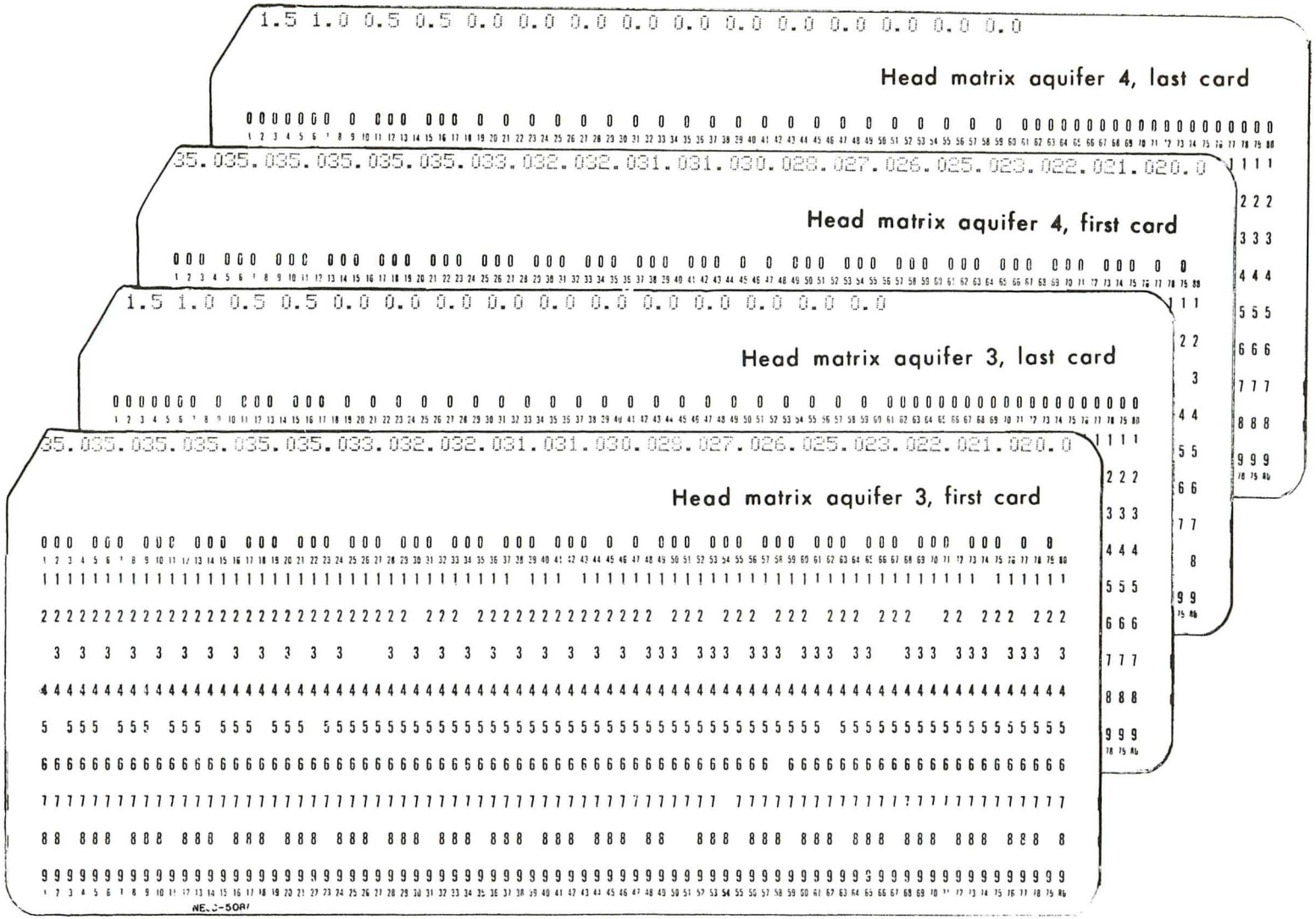

Figure 21. Data-deck setup: Head matrix (continued).

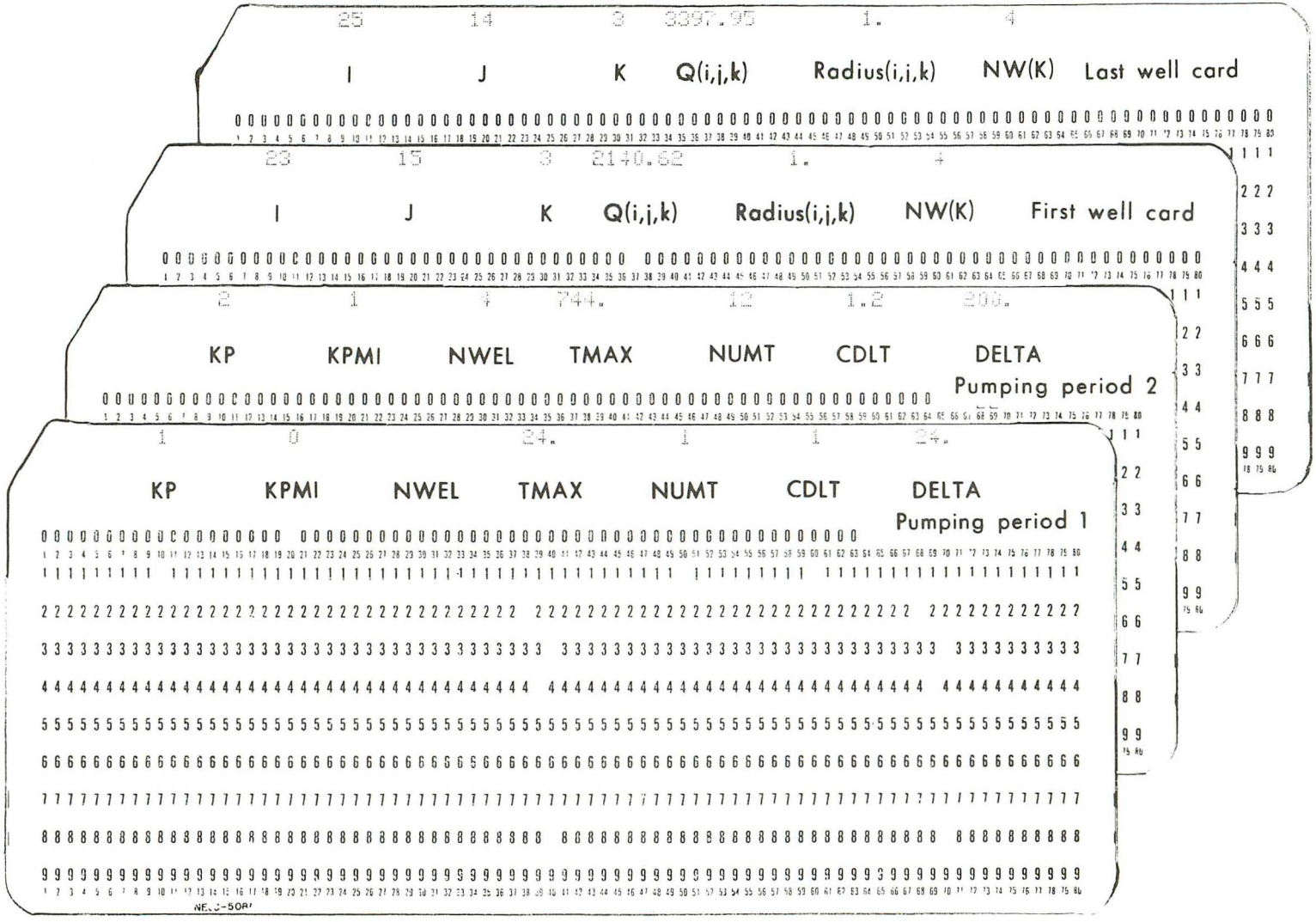

Figure 22. Data-deck setup: Pumping period and well cards.

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