THESIS

# NUMERICAL SIMULATION FOR CONVECTION OF CONTAMINANTS IN GROUNDWATER


Submitted by

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## ABSTRACT

A numerical model which simulates the convective transport of conservative ions through groundwater aquifers is presented and discussed. The model uses the fully implicit, central finite difference technique to predict transient, two-dimensional areal groundwater level or piezometric head fluctuations, the corresponding flows, and the convective transport of conservative ions. The model uses the fully explicit finite difference technique to calculate the contaminant concentrations. The model neglects the dispersion portion of the convective-dispersion equation. Either square or rectangular grids which remain constant throughout the study period may be used.

Simple longitudinal and radial flow problems are solved. In addition, criteria to assure convergence and stability of the model are developed theoretically and empirically. The sensitivity of the model to variations in grid size, time increment and seepage velocity are presented.

The study was limited to confined aquifers. However, the model has been developed to handle unconfined aquifers also. The study was also limited to homogeneous and isotropic porous media.

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# CHAPTER I

# INTRODUCTION

Water is the most abundant substance on earth. It is estimated that there is six times as much water on the earth as there is feldspar, the most abundant solid material. Of all the fresh water, approximately 97% -- about 8 trillion acre-feet -- is groundwater (Universal Oil Products, 1974).

Rapid population and industrial growth have led to extensive utilization of groundwater for municipal, agricultural, and industrial purposes. At the same time, improper disposal of human wastes, garbage and toxic chemicals, in addition to agricultural irrigation and fertilization, and a general unfamiliarity with groundwater hydrology have resulted in many instances of groundwater contamination.

These problems have finally begun to make officials aware of the potential for contamination of groundwater aquifers. The need for managing the quality of groundwater has also become apparent. In order to study and predict the areal distribution of contaminants in groundwater aquifers, it is necessary to understand the movement of the contaminants through the groundwater systems.

## Groundwater Quality Modeling and its Limitations

As a means to study the movement of contaminants in groundwater aquifers, numerical models using digital computers have been developed.

These models simulate the movement of groundwater with additional provisions to simulate the transport and dispersion of contaminants.

Recent attempts at developing groundwater quality models have been limited primarily to conservative substances, principally the mineral salts. While this simplifies the development process, it is not undesirable since certain conservative parameters (e.g. total dissolved solids, chlorides, etc.) are of significant interest to water quality agencies.

These water quality models generally model only one contaminant at a time. The models are normally two-dimensional simulating areal or vertical distribution of the contaminant. While many models ignore the effects of soil chemistry, some models (Water Resources Engineers, Inc., 1969, and Perez et al, 1972) take the effects of the unsaturated soil zone into account.

Various numerical techniques have been used in the attempt to simulate the convective transport and dispersion of contaminants in groundwater aquifers. The finite difference technique has been adapted using the fully explicit, fully implicit (including forward, centered, and backward in time approaches), and the alternating-direction methods for solution. Previous research has indicated that, while these methods are valid, large amounts of computer time and storage usually limit their application.

The finite element technique has been studied more recently because it supposedly has advantages over the finite difference technique. However, some studies have shown that the Rayleigh-Ritz method exhibits convergence and stability problems and is not applicable to cases where convection is the dominant transport mode. Another approach, the Galerkin method, requires large amounts of computer storage and time because small time steps and grid sizes must be used during the early calculations.

The method of characteristics is another numerical technique used to simulate convective transport and dispersion. Initial research where concentration values of the stationary grids were plotted indicated a significant amount of numerical dispersion. However, additional studies were made and accurate results obtained when the concentrations of the moving points were plotted.

## Objectives of this Study

The previous discussion indicates that serious limitations are inherent in most numerical methods used to simulate convection and dispersion in groundwater aquifers. Most of the models require that the coefficient of dispersion be known and that the users have an extensive understanding of numerical methods, groundwater hydrology and the convection-dispersion process. In addition, these models often require extensive field data and very large amounts of computer time and storage.

Sunada (McWhorter et al, 1977) presented a finite difference numerical model called WTQUAL1 which simulates the convective transport of conservative ions. This model simplifies the simulation of contaminant movement through groundwater aquifers by neglecting the dispersion process. The model ignores the effects of the unsaturated soil column and handles only one conservative parameter at a time. By using the fully explicit technique to calculate contaminant concentrations, the model minimizes the need for costly computer storage and time.

The objectives of this study are to:

1. Briefly discuss WTQUAL1, paying particular attention to the groundwater flow equation and the mass balance equation used to calculate the contaminant concentrations.
2. Modify WTQUAL1 so that it is applicable to a wider variety of problems.
3. Verify the numerical model by comparing numerical solutions to appropriate analytic solutions.
4. Develop criteria to assure convergence and stability of the model.
5. Perform a sensitivity analysis of the model, specifically evaluating those terms which appear in the stability criteria.

A review of literature dealing with numerical simulation of convection and dispersion in groundwater aquifers will be made. The problems encountered in these approaches will be noted and the effort of this study directed toward minimization or elimination of these problems. The existing numerical model will be modified and a hypothetical aquifer developed for which both numerical and analytic solutions for convection problems will be made. Computer runs will be made primarily on the HP 9830A desk-top computer with verification of these runs being made on the CDC 6400. Theoretical and empirical approaches will be used to develop criteria to assure convergence and stability of the model. Analyses will be performed to determine the sensitivity of the model to changes in grid size, length of time increment and seepage velocity. In addition, runs will be made to verify that the model produces accurate results for the two-dimensional convection process resulting from radial flow from a recharge well.

# CHAPTER II

## CONVECTION AND DISPERSION IN POROUS MEDIA

The first recorded study of dispersion in porous media was done inadvertently by Slichter (1905). In attempting to determine the rate of movement of groundwater, he injected a salt solution into a well and observed the time of arrival at an observation well down-gradient. He noted that the salt did not arrive at the observation well as a slug, but that the salt concentration gradually increased to some maximum value and then decreased. Since that time, much work has been done on the properties of dispersion and molecular diffusion of contaminants in groundwater.

Variation of concentration of contaminants in groundwaters is caused by three processes: convection, dispersion and molecular diffusion. Convection is the transportation of contaminants associated with groundwater flow and is based on the average seepage velocity. Dispersion in a porous media is associated with the convection process and results from a mechanical mixing caused by the individual fluid particles traveling at variable velocities through the pore spaces of the media and along microscopic path lines. Molecular diffusion results directly from the thermal motion of the individual fluid molecules and takes place under the influence of a concentration gradient. A detailed discussion of convection and dispersion is contained in Bear (1972).

Due to the difficulty encountered in trying to describe the boundary conditions on a microscopic scale (i.e. diffusion), the system is usually described on a macroscopic scale (i.e. convection and dispersion). Dispersion is a function of three physical properties: the fluid, the porous media, and fluid flow. Fluid properties of concern are density, viscosity, contaminant concentration, and miscibility of fluids in systems containing two or more fluid types. Media properties affecting dispersion are permeability, pore geometry, and pore space dimensions. Velocity is the major flow property.

According to Scheidegger (1961), and deJosselin deJong and Bossen (1961), the convection and dispersion of a contaminant in fluid flow through a saturated homogeneous porous medium is described by the differential equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left[ D_{ij} \frac{\partial C}{\partial x_j} - v_i C \right] \qquad (2\text{-}1)$$

where $D_{ij}$ = coefficient of dispersion

$C$ = the contaminant concentration

$t$ = time

$v_i$ = the component of the seepage velocity vector in a cartesian coordinate system, and

$x_i$ $(i=1,2,3)$ = the cartesian space coordinates.

The double subscripting of $D_{ij}$ and $x_i, x_j$ represent the tensorial nature of the dispersion process. The first term in brackets represents the dispersion process while the second term represents convection.

Analytic Solution of Longitudinal Convection and Dispersion

For longitudinal convection and dispersion in a homogeneous and isotropic porous medium with a plane source at $x_3=0$ (see Figure 2-1), Equation 2-1 becomes:

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x_3^2} - v_3 \frac{\partial C}{\partial x_3} \tag{2-2}$$

where $D_L$ is the longitudinal dispersion coefficient neglecting molecular diffusion. The initial and boundary conditions needed for the schematic in Figure 2-1 to apply for steady state flow in the direction of the velocity vector are as follows: the concentration $C=C_0$ of the contaminant source is constant for all times; the concentration in the porous media is initially zero for all values of $x_3$; the concentration at $x_3$ equal infinity is always zero. Mathematically, these initial and boundary conditions are given by:

$$\begin{aligned} C(0,t) &= C_0 \quad ; \quad t \geq 0 \\ C(x_3,0) &= 0 \quad ; \quad x_3 \geq 0 \\ C(\infty,t) &= 0 \quad ; \quad t \geq 0. \end{aligned} \tag{2-3}$$

Ogata and Banks (1961) used Laplace transforms to obtain the following solution to Equations 2-2 and 2-3:

$$\frac{C}{C_0} = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{x_3 - v_3 t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{v_3 x_3}{D_L}\right) \operatorname{erfc}\left(\frac{x_3 + v_3 t}{2\sqrt{D_L t}}\right)\right] \tag{2-4}$$

where erfc=1-erf. For areas not close to the source and where $x_3 > v_3 t$, the second term in Equation 2-4 can be omitted and the equation simplified to:

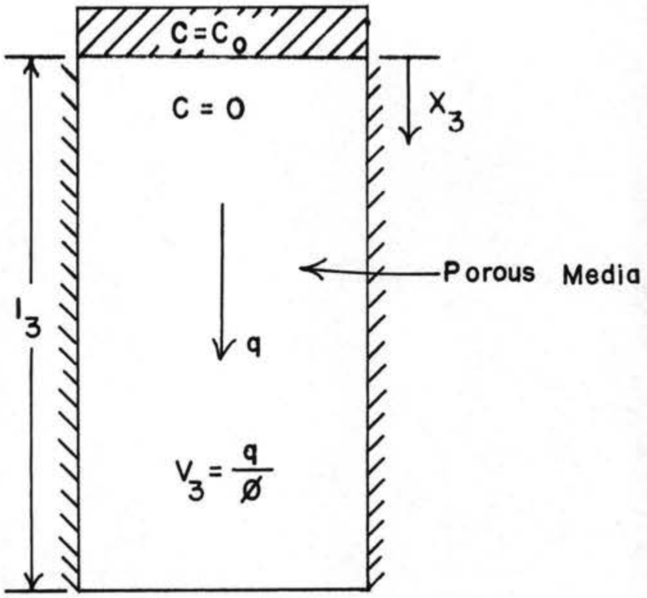


Figure 2-1. Schematic of longitudinal dispersion.

$$\frac{C}{C_0} = \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{x_3 - v_3 t}{2\sqrt{D_L t}}\right)\right] \tag{2-5}$$

Where $x_3 < v_3 t$, the applicable equation is:

$$\frac{C}{C_0} = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{x_3 - v_3 t}{2\sqrt{D_L t}}\right)\right] \tag{2-6}$$

Equations 2-5 and 2-6 assume that the dispersion is symmetric about the point $C/C_0=0.50$ and assume steady state flow but non-steady state dispersion.

Analytic Solution of Longitudinal and Lateral Dispersion and Longitudinal Convection

If the source area is less than the area through which flow is occuring, longitudinal and lateral dispersion and longitudinal convection will occur. A schematic of this condition is shown in Figure 2-2(a).

For a homogeneous and isotropic media with one dimensional flow in the $x_3$ direction only, the governing equation is:

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x_3{}^2} + D_T \frac{\partial^2 C}{\partial x_3{}^2} - v_3 \frac{\partial C}{\partial x_3} \qquad (2\text{-}7)$$

where $D_T$ is the lateral (transverse) dispersion coefficient. For steady state conditions and with flow in the direction of the velocity vector, the initial and boundary conditions for this equation are:

$$\left.\begin{array}{lll}
C(x_2,0,t) = C_0 & ; \quad 0 \leq x_2 \leq b \quad ; & t \geq 0 \\
C(x_2,0,t) = 0 & ; \quad b \leq x_2 \leq \ell_2 \quad ; & t \geq 0 \\
\dfrac{\partial C(0,x_3,t)}{\partial x_2} = 0 & ; \quad t > 0 & \\
\dfrac{\partial C(\ell_2,x_3,t)}{\partial x_2} = 0 & ; \quad t > 0 & \\
C(x_2,\infty,t) = \text{bounded} & & \\
C(x_2,x_3,0) = 0 & ; \quad 0 \leq x_2 \leq \ell_2 \quad ; & x_3 > 0
\end{array}\right. \qquad (2\text{-}8)$$

The actual dispersion process is graphically shown in Figure 2-2(b). Harleman and Rumer (1963) gave the following approximate steady state

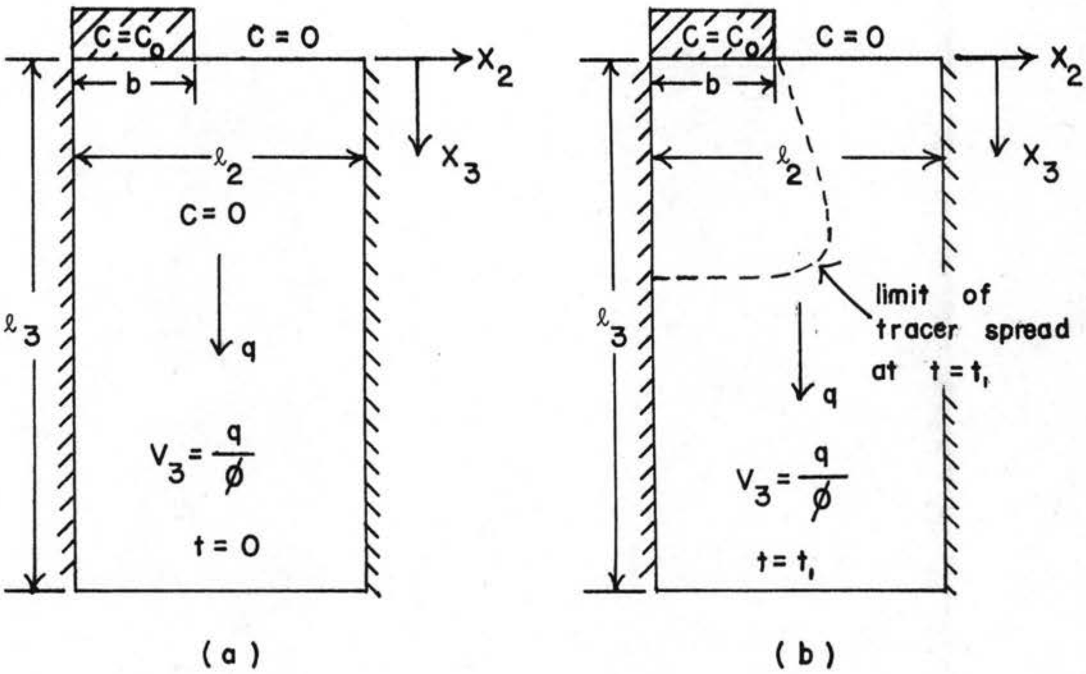


Figure 2-2. Schematic of longitudinal and lateral dispersion.

solution to Equations 2-7 and 2-8:

$$\frac{C}{C_0} = \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{x_3 - b}{2\sqrt{D_T \frac{x_3}{v_3}}}\right)\right] \tag{2-9}$$

Analytic Solution for Radial Convection and Dispersion

The partial differential equation governing radially symmetric diverging flow and the associated convection and dispersion from a well is (Bear, 1972):

$$\frac{\partial C}{\partial t} = va_I \frac{\partial^2 C}{\partial r^2} - v\frac{\partial C}{\partial r} \tag{2-10}$$

where $r$ is the radial distance from the recharging well and $a_I$ is the longitudinal dispersivity of the porous media expressed as the coefficient of dispersion $D_L$ divided by the seepage velocity $v$.

For a well of radius $r_w$ injecting a fluid at a constant rate into a confined aquifer, the initial and boundary conditions for Equation 2-10 are:

$$\begin{aligned} C(r,t) &= C_0 \quad ; \quad t > 0 \quad ; \quad r = r_2 \\ C(r,0) &= 0 \quad ; \quad r > r_w \\ C(\infty,t) &= 0 \quad ; \quad t > 0 \end{aligned} \tag{2-11}$$

Because of the nonlinearity of Equation 2-10 (resulting from the fact that $v$ is a function of $r$), exact analytic solutions are difficult to obtain. However, deJosselin deJong (Lau et al, 1959) obtained the following approximate analytic solution to Equation 2-10

$$\frac{C}{C_0} = \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{r - \bar{r}}{\sqrt{\frac{4}{3}\, a_I\, \bar{r}}}\right)\right] \tag{2-12}$$

where $\bar{r}$ is the average radius of the body of injected water.

Raimondi et al (1959) suggested an approximate solution to Equation 2-10 based on the assumption that the influence of dispersion becomes small in comparison to the local convective effect as the contaminant moves away from the source. They assumed that the influence of dispersion and diffusion on the concentration distribution as the contaminant moves past any point becomes small as compared to the accumulated effect of dispersion and diffusion that has taken place up to that point. For the case of a well continuously injecting a contaminant of constant concentration they derived the equation:

$$\frac{C}{C_0} = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{r^2/2 - Gt}{\sqrt{\frac{4}{3} a_I \overline{r^3}}} \right) \right] \tag{2-13}$$

where $G$ is obtained from the relationship

$$G = \frac{Q}{2\pi h\phi} = vr \tag{2-14}$$

where $h$ is the saturated thickness of a confined aquifer, $v$ is the seepage velocity and $\phi$ is the porosity.

Dispersion Coefficients

Ebach and White (1958) developed the following empirical relationship for the longitudinal dispersion coefficient based on experiments over a wide range of particle sizes and shapes and where the Reynolds numbers ($\mathbb{R}$) were less than 100:

$$\frac{D_L}{\nu} = \alpha_1 \left(\frac{vd}{\nu}\right)^{\beta_1} \tag{2-15}$$

where $(\frac{vd}{\nu})$ = the Reynold's number $\mathbb{R}$

$v$ = the fluid velocity

$d$ = the particle size of the porous media

$\nu$ = the kinematic viscosity of the fluid

$\alpha_1$ and $\beta_1$ = porous medium coefficients.

They found that $\alpha_1$ is strongly dependent on the porous medium while $\beta_1$ is a function of the flow regime and the porous medium. Various experimental values for $\alpha_1$ and $\beta_1$ have been obtained and are listed in Table 2-1.

TABLE 2-1. Experimentally Determined Values for $\alpha_1$ and $\beta_1$

| Reference | $\alpha_1$ | $\beta_1$ |
|---|---|---|
| Harleman and Rumer (1963) | 0.66 | 1.2 |
| Hoopes and Harleman (1965) | 1.70 | 1.2 |
| Ebach and White (1958) | 1.92 | 1.06 |

Harleman et al (1963) also correlated the longitudinal dispersion coefficient with intrinsic permeability and obtained the following empirical relationship:

$$\frac{D_L}{\nu} = \alpha_2\left(\frac{v\sqrt{k}}{\nu}\right)^{\beta_2} \qquad (2\text{-}16)$$

where k is the intrinsic permeability. They found $\alpha_2$=54 for spheres and 88 for sand with $\beta_2$=1.2 for both media.

Attempts to fit the lateral dispersion coefficient into a form similar to Equation 2-15 led to the following equation:

$$\frac{D_T}{\nu} = \alpha_3\left(\frac{vd}{\nu}\right)^{\beta_3} \qquad (2\text{-}17)$$

Experimental values for $\alpha_3$ range from 0.036 (Harleman and Rumer, 1963) to 0.11 (Hoopes and Harleman, 1965). Both studies estimated $\beta_3$ to be 0.7.

Review of Finite Difference Simulation Techniques

Numerical methods approximate the governing differential equations, allowing for high speed solution of a set of equations. While the use of analytic solutions is limited to simplistic problems, the numerical models can be applied to problems involving many source or sink terms and a variety of boundary conditions. To verify the validity of a numerical scheme, it is necessary to compare numerical and analytic solutions for the same problems. A discussion of numerical methods is contained in Conte (1965).

Douglas, Peaceman and Rachford (1959) solved the problem of miscible displacement in a two-dimensional flow field using an alternating-direction implicit scheme. This work was expanded on by Peaceman and Rachford (1962) and by Blair and Peaceman (1963). Two significant problems were often encountered: either the results were effected by numerical dispersion or the solution developed severe oscillations, especially in the regions where the concentration changed rapidly. Numerical dispersion is the error associated with the numerical approximation of the governing differential equation.

In an effort to overcome the problems of instability and numerical dispersion, Stone and Brian (1963) developed a method which consisted of writing a general finite difference equation for the one-dimensional convective-dispersion equation. Their method contained arbitrary weighting coefficients for approximations to the space and time derivatives of the contaminant concentration. With proper choice of weighting coefficients, the model did reduce oscillations and numerical dispersion but could not handle two- and three-dimensional problems.

Shamir and Harleman (1966) took advantage of the Stone and Brian scheme by transforming the two-dimensional dispersion equation into a potential flow coordinate system (i.e., equipotential and streamlines). In this case, the velocity is everywhere tangential to the streamlines and the equation becomes one-dimensional in the convective term. They observed that $C/C_0$ values greater than 1.0 occurred behind the dispersion front. While the method did exhibit this oscillation, the solution was considered stable since the magnitude of the oscillation was constant with time.

Shamir and Harleman also discussed several basic finite difference approaches of simulating the movement of contaminants in groundwater aquifers. They stated that the fully explicit method of calculating the contaminant concentrations was impractical due to the large amounts of computer time required to solve even very simple problems. They determined that the grid size in the direction of flow must be on the order of a single grain size. They also concluded that the maximum admissible time increment was of the order required for the mean velocity to cover a distance equal to a fraction of the grain size. This particular numerical scheme required that the coefficient of dispersion be known to solve the dispersion equation.

Review of Finite Element Simulation Techniques

The finite element technique supposedly has several advantages over the finite difference technique. Chief among these are the use of smaller amounts of computer time and less storage, additional flexibility available to model irrigular shaped basins by using triangular grids as opposed to square or rectangular grids, and a minimizing of numerical dispersion. Whereas the finite difference technique solves the dispersion equation directly, the finite element technique uses a functional which is minimized for each triangular element. The resulting set of equations is then solved.

Price, Cavendish and Varga (1968) used the Galerkin method for solution of the one-dimensional diffusion-convection equation. They obtained more accurate results while requiring less computer time than central or non-central finite difference approximations and the method of characteristics.

Guyman (1970a) applied the Rayleigh-Ritz finite element technique to the solution of the nonsteady state one-dimensional diffusion-convection equation and later extended it to the two-dimensional case (1970b). The method was not applicable to problems defined by mixed partial differential equations. Later, Guyman (1972) suggested an improvement to his previous solution of the convective dispersion equation but that method displayed numerical dispersion and gave erratic results for small values of the dispersion parameters. It was concluded that the method was not applicable to convection dominated mass transport.

The efforts by Guyman and additional work by Nalluswami (1971) suggested that the method could not be applied to convection dominated transport which is the case for a majority of field situations. In addition, the time domain solution was comprised of inherently explicit schemes and so exhibited convergence and stability problems.

Prakash (1974) applied the Galerkin method to the flow of salt water towards partially penetrating wells located in homogeneous and isotropic aquifers consisting of a fresh water layer overlying a salt water layer. He found that in order to prevent oscillations in the solution of the flow equation, small initial time steps must be followed by gradually increasing time step size. He also found that the number of elements required for reasonably accurate results with a linear interpolation function has to be very large, necessitating huge amounts of computer storage. Due to the combined effect of small initial time steps and the large number of elements, the number of iterations to be performed becomes very large.

## Review of Method of Characteristics Simulation Technique

Garder, Peaceman and Pozzi (1964) used the method of characteristics to solve the problem of miscible displacement of an oil-solvent system in order to reduce numerical dispersion. The method gave good results for low oil-solvent viscosity ratios but ignored the tensorial nature of dispersion. However, the method required large amounts of computer time and storage while giving results slightly more accurate than previous, cheaper methods.

Reddell and Sunada (1970) developed flow and convective dispersion equations for non-homogeneous, unsteady flow fields. The flow equation was solved using an implicit numerical technique and the convective dispersion equation was solved using the method of characteristics. This technique required so much excessive storage to catalog information on each moving point that auxilliary storage was required. They observed that the magnitude of error did not converge to a minimum value regardless of the number of points used per grid in the simple one-dimensional case. They also observed that the concentration profile lagged the actual frontal movement when the moving points remained inside a grid throughout a time step. Use of a weighted-average in the concentration calculations and taking the tensorial nature of dispersion into account allowed for more accurate calculations.

Kraeger (1972) applied the method of characteristics as developed by Reddell and Sunada to a field problem. She observed numerical dispersion inherent in the method of characteristics which did not show up in Reddell and Sunada's study. She attributed this to the grid size used. Reddell and Sunada used grids on the order of fractions of centimeters in size, allowing the actual physical dispersion to partially absorb the numerical smear. Kraeger used grids approximately one-half mile square which clearly indicated the numerical dispersion. She also encountered difficulty in trying a trial-and-error process to arrive at a time increment which produced a concentration distribution resembling the data collected in the field.

Shariatmadar Taleghani (1974) used the method of characteristics to solve the convective-dispersion equation for the case of partially penetrating wells pumping from an aquifer consisting of a fresh water layer underlain by salt water. He obtained accurate results when the concentrations of the moving points were plotted. Kraeger had plotted the concentrations of the stationary grids while neglecting the dispersion process. Therefore, she whould have obtained a vertical front regardless of the value of the dispersion coefficient. Shariatmadar Taleghani concluded that the numerical dispersion which Kraeger noted was a result of the manner in which she plotted the concentration distribution curves and not the grid size used.

Summary of Previous Research

The development of the analytic solutions for dispersion in porous media were major accomplishments. However, their applicability to physical situations is severely restricted. The effect of boundary conditions and inability to handle more than one contaminant source are serious limitations.

The numerical methods which have been developed offer a significant improvement over the analytic solutions but have their own limitations. These methods often require large amounts of costly computer time and storage. Many of the models are affected by instability. In addition, some models require extensive physical data such as longitudinal and lateral dispersion coefficients which are often economically impossible to obtain or which simply are unavailable.

# CHAPTER III

# THE GROUNDWATER QUALITY MODEL

The groundwater staff of the Civil Engineering Department at Colorado State University recognized the need to develop a numerical approach to simulate two-dimensional flow in aquifers consisting of multiple sources and sinks. The basic philosophy of the model was presented in Bittinger et al (1967). Eckhardt (1976) modified the model to handle confined and unconfined leaky aquifers. Sunada (McWhorter et al, 1977) added provisions to simulate the convection of conservative water quality parameters and called the model WTQUAL1.

## Groundwater Flow Equation

The basic non-linear partial differential equation describing two-dimensional transient flow in a saturated porous medium may be derived from the mass continuity equation and Darcy's Law and written as (Jacob, 1950):

$$\frac{\partial}{\partial x}\left(K_x h\ \Delta y\ \frac{\partial H}{\partial x}\right)\Delta x + \frac{\partial}{\partial y}\left(K_y h\ \Delta x\ \frac{\partial H}{\partial y}\right)\Delta y = S\ \frac{\partial h}{\partial t}\ \Delta x\ \Delta y + Q \qquad (3\text{-}1)$$

where h = saturated thickness of aquifer (L)

H = water table elevation above datum (L)

K = hydraulic conductivity (L/T)

S = storage coefficient (dimensionless)

Q = net groundwater withdrawal ($L^3/T$)

$x,y$ = space dimensions (L)

$t$ = time dimension (T).

Equation 3-1 has no general solution. However, by making use of the grid system shown in Figure 3-1, a finite difference approximation of this equation will allow a numerical solution. Equation 3-1 written in implicit, central finite difference form is as follows:

$$[AH_{i,j-1} + BH_{i,j+1} + CH_{i-1,j} + DH_{i+1,j} - (A+B+C+D+E)H_{i,j}]^{t+\Delta t}$$

$$= Q - EH^{t}_{i,j} \qquad (3\text{-}2)$$

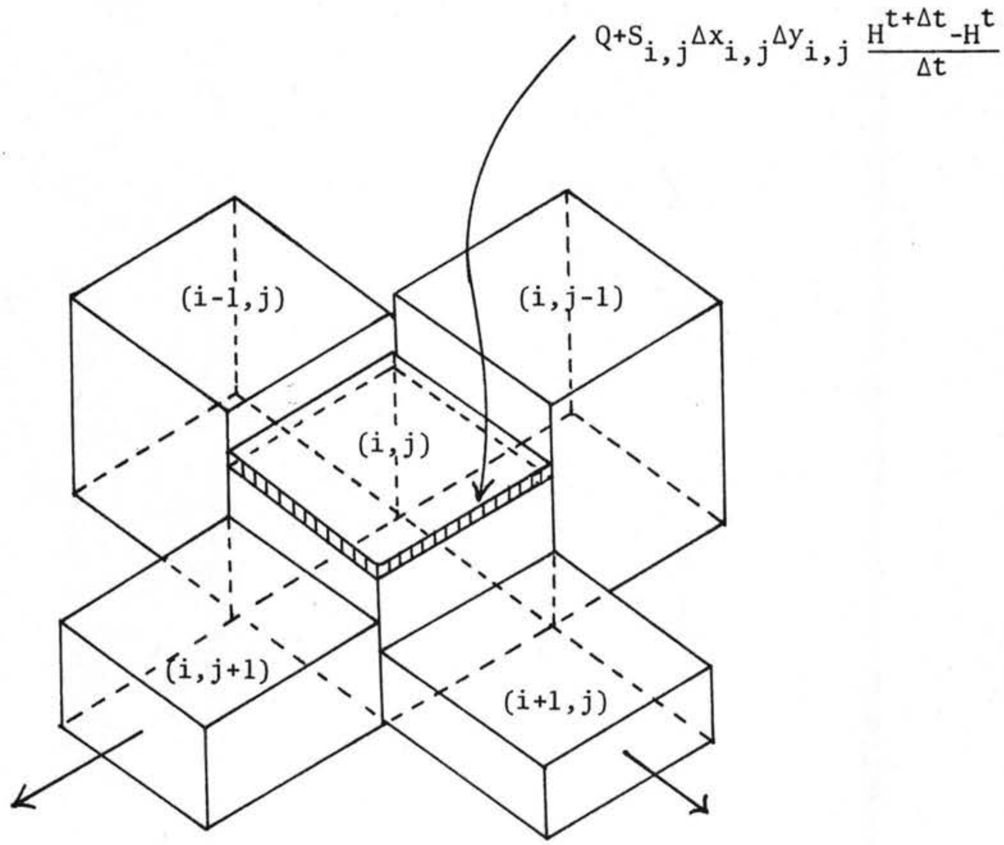


Figure 3-1. Finite difference grid notation (adapted from Bittinger, et al).

where,

$$A = \frac{2K_{i,j} \cdot K_{i,j-1} \cdot \Delta y_{i,j} \cdot \Delta y_{i,j-1} \cdot h_{i,j-1/2}}{\Delta y_{i,j} \cdot K_{i,j} \cdot \Delta x_{i,j-1} + \Delta y_{i,j-1} \cdot K_{i,j-1} \cdot \Delta x_{i,j}}$$

$$B = \frac{2K_{i,j} \cdot K_{i,j+1} \cdot \Delta y_{i,j} \cdot \Delta y_{i,j+1} \cdot h_{i,j+1/2}}{\Delta x_{i,j} \cdot K_{i,j+1} \cdot \Delta y_{i,j+1} + \Delta x_{i,j+1} \cdot K_{i,j} \cdot \Delta y_{i,j}}$$

$$C = \frac{2K_{i,j} \cdot K_{i-1,j} \cdot \Delta x_{i,j} \cdot \Delta x_{i-1,j} \cdot h_{i-1/2,j}}{\Delta y_{i,j} \cdot K_{i-1,j} \cdot \Delta x_{i-1,j} + \Delta y_{i-1,j} \cdot K_{i,j} \cdot \Delta x_{i,j}}$$

$$D = \frac{2K_{i,j} \cdot K_{i+1,j} \cdot \Delta x_{i,j} \cdot \Delta x_{i+1,j} \cdot h_{i+1/2,j}}{\Delta y_{i,j} \cdot K_{i+1,j} \cdot \Delta x_{i+1,j} + \Delta y_{i+1,j} \cdot K_{i,j} \cdot \Delta x_{i,j}}$$

$$E = \frac{S_{i,j} \cdot \Delta x_{i,j} \cdot \Delta y_{i,j}}{\Delta t}$$

Equations 3-1 and 3-2 are subject to the Dupuit-Forchheimer assumptions and also assume that the fluid and porous medium are incompressible.

The subscript notation refers to particular grid blocks in a five-grid system as indicated in Figure 3-1. The superscript $t$ refers to the starting time or previous time level, $\Delta t$ is the time increment and $t+\Delta t$ is the current time level. Equation 3-2 is written for each grid in the study area for each designated time increment. The system of equations for the first time increment is solved simultaneously for the values of $H_{i,j}$ at the end of the time increment. These computed values of $H_{i,j}$ are then used as initial values in the system of equations representing the next time increment.

The coefficients A, B, C, and D are computed for each grid at the beginning of each time increment and are held constant during the time increment. The term $(h_{i,j-1/2})$ in the equation for coefficient A is the effective saturated thickness between grids (i,j-1) and (i,j) calculated by the following approximation:

$$h_{i,j-1/2} = MAX(H_{i,j}, H_{i,j-1}) - MAX(Z_{i,j}, Z_{i,j-1}) \tag{3-3}$$

where Z equals the bedrock elevation above a datum. A similar expression may be written for the h term in the equations for the coefficients B, C, and D. The value for the storage coefficient, S, included in coefficient E, various spatially but remains constant in time. If the time increment is also constant, coefficient E will remain constant in time for each grid.

The rate of net groundwater withdrawal, Q, represents the deep percolation of precipitation and applied surface water, and the rate of net withdrawal by pumping. The extraction of water by phreatophytes or the addition of water by artificial recharge could also be included in the value of Q. It is necessary to calculate an average value of Q for each grid for each time increment.

Water Quality Aspects of WTQUAL1

WTQUAL1 was developed primarily to model the convection of contaminants which are picked up when water flows through strip mine tailings. The model allows for a continuous contaminant source in those cases where the contaminants go into solution over a long period of time. The model considers as slug sources those cases where the contaminants go into solution in a relatively short period of time.

WTQUAL1 uses the fully explicit method to determine relative contaminant concentrations during each time increment. However, the model only allows consideration of water quality parameters within the aquifer itself. Other contaminant sources such as rivers, lakes, irrigated land and artificial recharge areas cannot be considered when using WTQUAL1.

The fully explicit method, which assumes complete and instantaneous mixing of the waters in the aquifer, satisfies the objective of a simplistic convective transport simulator. In addition, the fully explicit method as utilized in WTQUAL1 provides results of sufficient accuracy to render the numerical simulator a valid approach.

Since it was desirable to develop a simplistic simulator of convection in groundwater aquifers, it was felt that WTQUAL1 offered an excellent starting point. Because WTQUAL1 was based on a groundwater flow model, all the required inputs and outputs of the groundwater system, the geologic parameters and a provision for either slug or continuous contaminant injection were available. The primary modification required was to make provisions for including and varying input contaminant concentrations for each source variable for each desired time increment to be studied. This involves estimating relative concentrations of contaminants in rainfall, water applied as irrigation, constant head sources (e.g., lakes, rivers, ponds), artificial recharge areas, and the underflow into the aquifer from outside the area being studied.

## Modifications to WTQUAL1

The first modification to WTQUAL1 involved providing for the input of initial contaminant concentrations for all source waters. This was accomplished by expanding Subroutine READPH (see Appendix B for a flowchart of the computer program and Appendix C for a description of all subroutines). Provisions were made for reading in, as either slug or continuous sources, initial contaminant concentrations for precipitation, water applied as irrigation, water artificially recharged to the aquifer, and constant head sources such as rivers, lakes and ponds. These initial concentrations can be input as a constant throughout the study area or can be varied from grid to grid.

The second modification, which is actually an extension of the previous one, involved providing for the change of the contaminant concentrations of all the source waters at each time increment of analysis. This was accomplished by adding Subroutine READC to the program. A controlling variable, AGGIE, is included in the initial data input to the numerical model. Depending on the value of AGGIE, the model either uses the initial contaminant concentrations for each time increment of analysis or control is transferred to READC at the beginning of each time increment and new relative concentration values are read in. Concentrations for flows through boundary grids into the study area are included in this data input.

The next modification occurred in Subroutine QFIX. In order for the relative contaminant concentration calculation to be made later in the program, it was necessary to convert all flows to a consistent volumetric unit and to identify and store this volume for each source and sink for each grid in the study area. These terms are then retrieved by Subroutine BYFLØW where the actual concentration calcuations are made.

Due to the structure of Subroutine BYFLØW, the concentration calculation process was broken into two steps. First, an intermediate change in contaminant mass for the current time level was computed based on all source and sink terms except constant head grids. This step includes the actual flow of groundwater within the aquifer. Then, all constant head contributions to each grid were calculated. A new total change in contaminant mass was computed, converted to a relative concentration value and combined with the relative concentration value at the previous time step to give the new relative concentration value for each grid.

For confined aquifers, the model automatically excludes contaminants resulting from precipitation, water applied as irrigation, water artificially recharged to the aquifer, and phreatophyte consumption. However, contaminants removed by pumping and added by constant head sources in direct contact with the aquifer are included.

These modifications make the numerical model suitable for application to many problems involving either confined or unconfined aquifers. This modified version of WTQUAL1 is called WTQUAL2.

## Explicit Contaminant Mass Balance Equation

The fully explicit mass balance equation used in calculating the contaminant concentrations is very similar to that used in the development of the basic groundwater flow equation. In general terms, the mass balance equation can be written as:

$$\begin{bmatrix} \text{RATE OF CHANGE} \\ \text{OF CONTAMINANT} \\ \text{IN THE AQUIFER} \end{bmatrix} = \begin{bmatrix} \text{RATE OF CONTAMINANT} \\ \text{INFLOW TO THE} \\ \text{AQUIFER} \end{bmatrix} - \begin{bmatrix} \text{RATE OF CONTAMINANT} \\ \text{OUTFLOW FROM THE} \\ \text{AQUIFER} \end{bmatrix} \tag{3-4}$$

where the assumption is made that the rate of contaminant removal within the aquifer is zero (i.e. we are modeling a conservative substance).

The grid system used is identical to that shown in Figure 3-1. However, for more detailed illustration, a typical grid is shown in Figure 3-2 indicating the various parameters which effect the mass balance calculation. Neglecting the dispersion process, the applicable explicit mass balance equation in finite difference form is:

$$C_{i,j}^{t+\Delta t} = C_{i,j}^{t} + [(V^{t+\Delta t} \cdot C^{t})_{i,j-1} + (V^{t+\Delta t} \cdot C^{t})_{i-1,j} - V_{i+1,j}^{t+\Delta t} \cdot C_{i,j}^{t}$$

$$- V_{i,j+1}^{t+\Delta t} \cdot C_{i,j}^{t} + (W \cdot C)_{i,j}^{t+\Delta t} - VLEAK_{i,j}^{t+\Delta t} \cdot C_{i,j}^{t}] \;/\; [U_{i,j}^{t+\Delta t}] \qquad (3\text{-}5)$$

where $C_{i,j}$ = relative contaminant concentration in the grid i,j

$V_{i,j-1}$ = volume of flow from grid i,j-1 to grid i,j

$C_{i,j-1}$ = relative contaminant concentration corresponding to $V_{i,j-1}$

$V_{i-1,j}$ = volume of flow from grid i-1,j to grid i,j

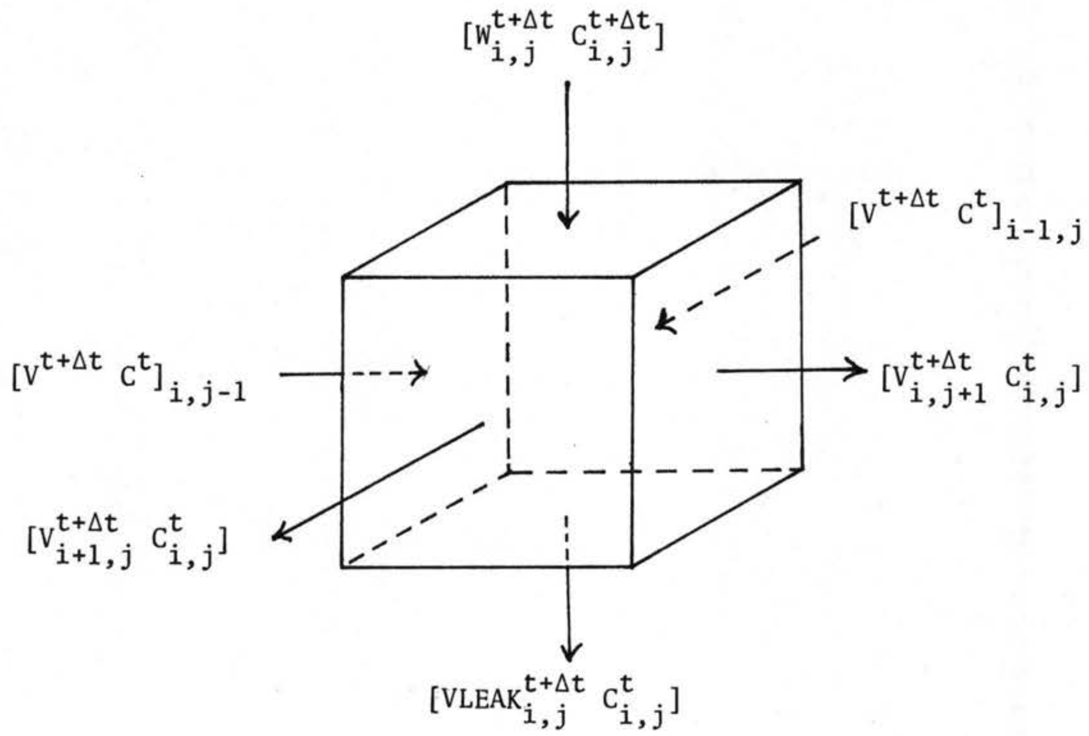


Figure 3-2. Typical aquifer grid illustrating parameters which influence a change in concentration.

$C_{i-1,j}$ = relative contaminant concentration corresponding to $V_{i-1,j}$

$V_{i+1,j}$ = volume of flow from grid $i,j$ to grid $i+1,j$

$V_{i,j+1}$ = volume of flow from grid $i,j$ to grid $i,j+1$

$VLEAK_{i,j}$ = volume of flow from grid $i,j$ through the leaky layer beneath the grid (applicable only if leaky aquifer conditions exist)

$U_{i,j}$ = total volume of water stored in grid $i,j$.

The term $(W \cdot C)_{i,j}^{t+\Delta t}$ is determined from the following relationship:

$$(W \cdot C)_{i,j}^{t+\Delta t} = [(V \cdot C)_{PPT} + (V \cdot C)_{RCHR} + (V \cdot C)_{APW} + (V \cdot C)_{SQR} - (V \cdot C)_{PHR} - (V \cdot C)_{PUM}]_{i,j}^{t+\Delta t} \qquad (3\text{-}6)$$

where the volumes, V, and relative contaminant concentrations, C, apply to precipitation (PPT), artificial recharge (RCHR), water applied as irrigation (APW), recharge from constant head sources such as rivers, lakes and ponds (SQR), phreatophyte consumption (PHR), and pumping from wells (PUM). This equation encompasses the modifications made to WTQUAL1 allowing the contaminant concentrations of all source and sink waters to be taken into account.

## Description of the Numerical Model

WTQUAL2 uses the fully implicit, central difference technique to predict transient, two-dimensional areal groundwater level (or piezometric head) fluctuations and the corresponding flows. Based upon these flows, the model uses the fully explicit mass balance technique to simulate the convection of contaminants through the aquifer.

The study area is overlain with a grid system. The selection of grid dimensions are dependent upon the stability criteria of the concentration calculation (see Chapter IV). The rectangular grid system is oriented to allow for easy boundary approximation, provide for easy adaption of hydrologic and geologic data, and to meet the required stability criteria.

The program reads in the number of rows and columns for the entire grid system, including those of the buffer zones which are built into the program (Olson, 1973). The desired time increment of analysis, total time of analysis, and time increment printout are also input to the program.

The dimensions of each grid and values for hydraulic conductivity, bedrock elevation, ground surface elevation, storage coefficient or specific yield, coefficient for the fraction of each grid that is irrigated, initial relative concentrations for all source waters, and initial relative concntrations for each of the grids in the aquifer are read as input data. All values are held constant throughout the time of analysis except for source water concentrations which may be changed at the beginning of each time step. New values of the aquifer concentrations are calculated for each time increment based on the previous concentration of each grid and the addition or loss of contaminant during the time period $\Delta t$.

Contaminant concentrations are read in and calculated as relative concentrations ranging from 0.0 to 1.0. Normally, a source concentration is considered to have a value of 1.0. However, if concentrations are anticipated which might exceed a source concentration, then an arbitrary value can be assigned to the relative concentration value of 1.0 and all other values will be referenced to it.

The initial water table (or piezometric head) elevations are also read in for each grid. Impermeable boundary grids, constant head boundary grids, and grids with horizontal underflow are identified by coding the initial water table elevations. For boundary grids having underflow, the difference in water elevation between the outermost boundary grid and the next inner grid is held constant throughout the total time of the analysis (i.e., a constant hydraulic gradient is maintained).

The program also reads in hydrologic data for annual precipitation (the model assumes a uniform depth of precipitation over the entire study area), annual water applied as irrigation (the model assumes a uniform application of the water over the irrigated portion of the grid in question), annual phreatophyte extraction, gross annual pumping withdrawal, and annual application of water to recharge pits. The annual precipitation, irrigation, phreatophyte, pumping, and recharge values are read in for each grid of the study area for the year to be analyzed. One set of annual distribution coefficients is read in for each of the five types of hydrologic data. The coefficients represent the percentage of annual precipitation, irrigation, phreatophyte consumption, pumping, and recharge that occurs during each of the time increments. The coefficients are read in initially and remain constant throughout one year of analysis but may be changed at the beginning of each additional year of analysis.

The program also reads in coefficients that represent the percentage of precipitation, applied water, and recharge water that percolates to the water table. Another coefficient is read in to represent the percentage of the gross pumping withdrawal that does not return to the water table.

The program uses the Gauss elimination method to solve the system of equations for each time step. The program output at desired time steps includes the following:

1. Matrix of net vertical withdrawal of water from each grid including precipitation, applied water, pumping, artificial recharge, phreatophyte consumption and leakage.
2. List of overdrawn or flooded grids.
3. List of grids, if any, which change from confined to unconfined or unconfined to confined.
4. Matrix of discharge between grids in the i-directions. Flow down is considered positive and flow upward is negative. Discharge in the first row of the matrix is the flow between grids in row 1 and 2, and so on for the remainder of the grids. Therefore, the value in the last row is always zero.
5. Matrix of discharge between grids in the j-direction. Flow right is positive and flow left is negative. Discharge in the first column of the matrix is the flow between grids in column 1 and 2 and so on for the remainder of the grids. Therefore, the value in the last column is always zero.
6. Matrix of net flow from constant head grids.

7. Table of water balance computations.

8. Matrix of water table or piezometric head elevations.

9. Matrix of relative contaminant concentrations.

# CHAPTER IV

# NUMERICAL SIMULATION OF CONVECTIVE TRANSPORT

As mentioned in the introduction, a major purpose of this research was to study a simplistic numerical technique to simulate convection of contaminants in groundwater aquifers. This attempt at a simplistic model is based on the fully explicit method of calculating contaminant concentrations. In order to compare numerical and analytic results, the aquifer studied must have both numerical and analytic solutions.

A hypothetical one-dimensional, homogeneous and isotropic, steady state situation was developed using representative values of aquifer properties for a coarse sand commonly encountered in actual physical situations (McWhorter and Sunada, 1977). The assumptions and calculations associated with the development of the hypothetical situation are discussed in Appendix A and a schematic of the layout is shown in Figure 4-1. In order to assure that flow was steady state, the saturated thickness of the aquifer was held constant and a constant hydraulic gradient was maintained.

## Verification of the Longitudinal Convection Case

The longitudinal convection case was verified using a one-dimensional, steady state flow situation with a constant contaminant source located along the inflow boundary of the model. Hydraulic conductivity was uniform throughout the model and the piezometric head was oriented to provide a constant gradient in the direction of flow

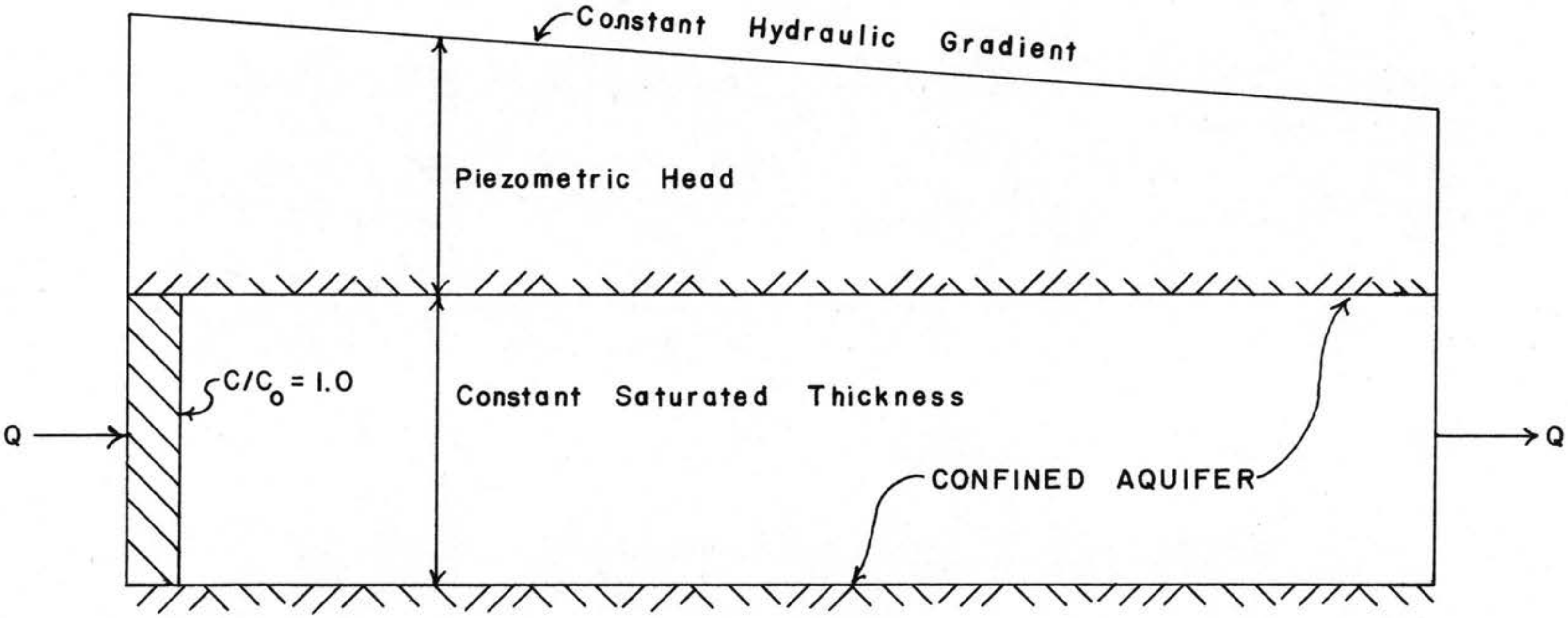


Figure 4-1. Schematic of the hypothetical aquifer with constant contaminant source.

and zero gradient perpendicular to the direction of flow. Boundaries parallel to the direction of flow were considered impermeable. This results in a constant seepage velocity $v$ being maintained throughout the aquifer in the direction of flow.

The numerical results were compared with those derived from Equations 2-5 and 2-6. The results for time equal 90, 180, 270, and 360 days and grid size equals 115 feet for a time increment of 30 days and grid size equals 40 feet for a time increment of 10 days are shown graphically in Figures 4-2 and 4-3, respectively.

The analytic solution is at all times located a distance equal to the product of the seepage velocity and the elapsed time from the contaminant source. The numerical solution satisfies this condition for the case where $C/C_0$ has a value of approximately 0.5.

The numerical model yielded relative concentration values which decreased gradually with increasing distance from the contaminant source. The shape of the numerically determined curve can be attributed to the numerical dispersion inherent in the model. This numerical dispersion is a result of the error which occurs from numerically approximating the governing differential equation. It is a function of the numerical model and is independent of the aquifer properties.

The abrupt change of the analytic solutions shown in Figures 4-2 and 4-3 is a result of neglecting the dispersion process. Therefore, the curves shown are actually vertical lines. The analytic solutions including the dispersion process were calculated but not plotted. The shape of these curves could not be distinguished from the curves neglecting the dispersion process.

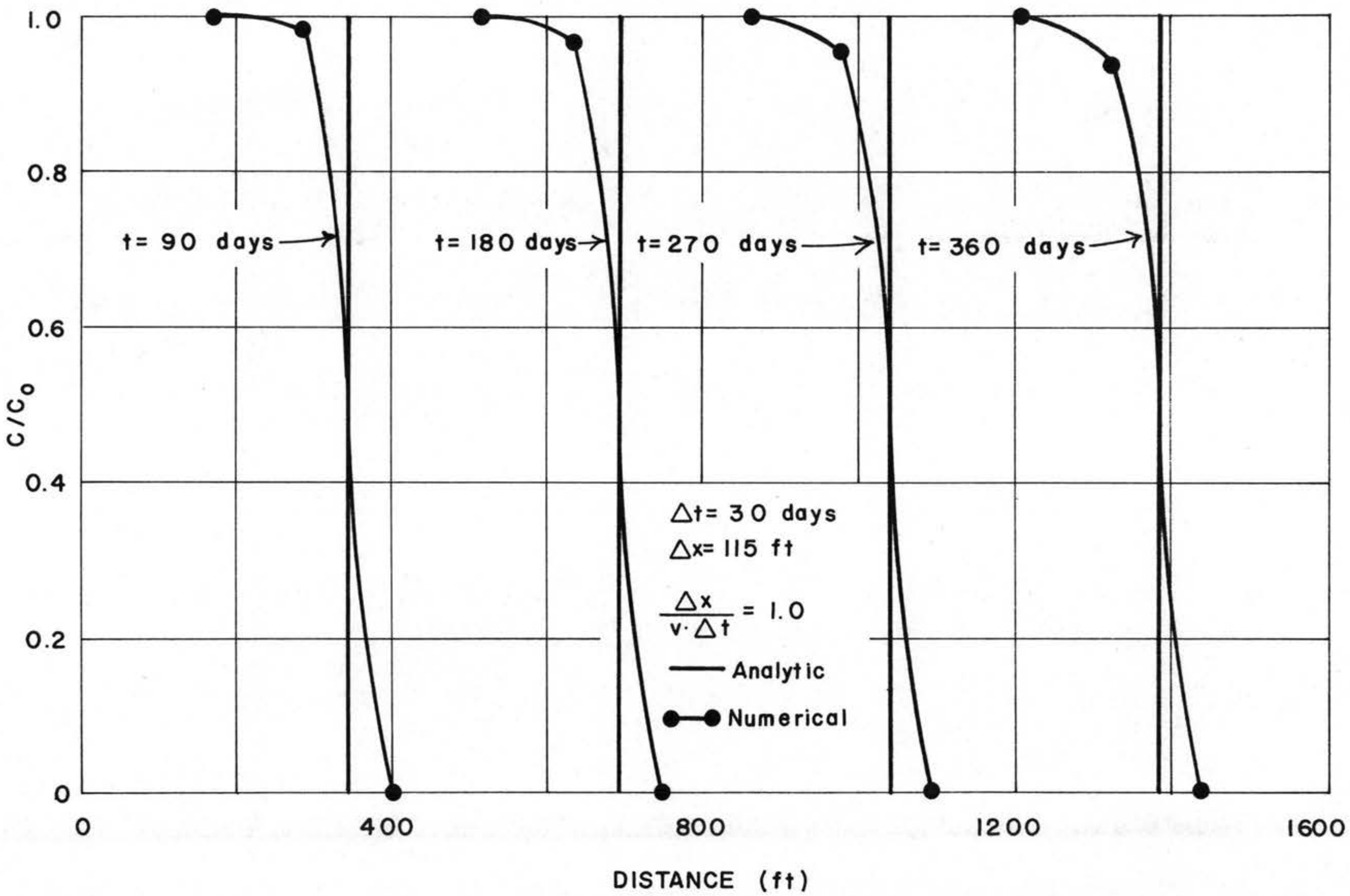


Figure 4-2. Numerical versus analytic solutions for $\Delta x/v\Delta t=1$ and $\Delta t=30$ days.

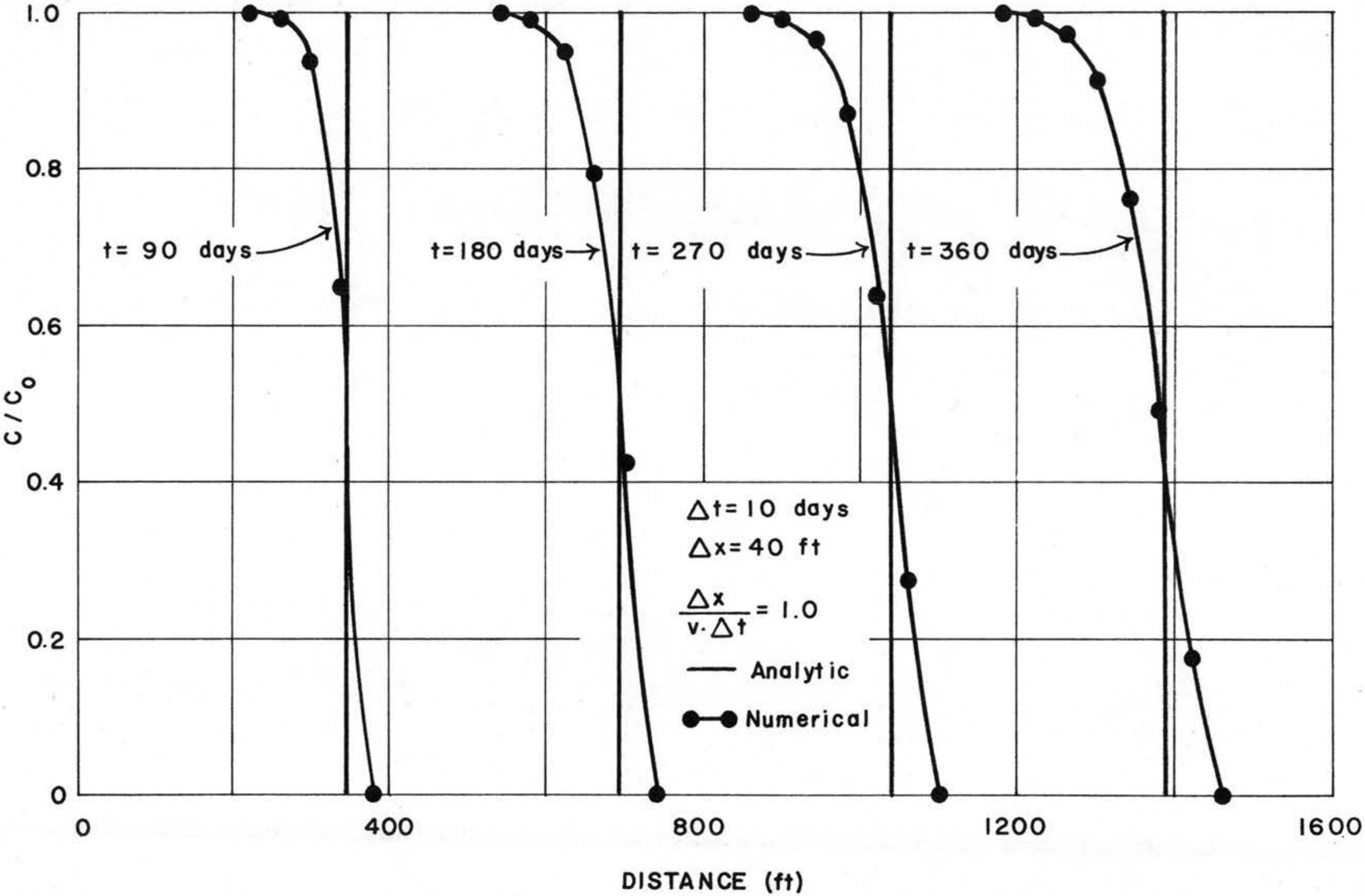


Figure 4-3. Numerical versus analytic solution for $\Delta x/v\Delta t=1$ and $\Delta t=10$ days.

Previous research indicates that analytic solutions are usually S-shaped curves similar to the numerical solutions shown. The seepage velocities and the associated dispersion coefficients for the analytic solutions used in this study are typical for actual physical situations and are low relative to those used by many previous researchers. As a result, the analytic solutions take on essentially vertical profiles.

The results shown in Figures 4-2 and 4-3 indicate that the method used to calculate the relative concentrations of the contaminant is a valid method, especially in the region near the point where $C/C_0=0.5$. For the particular cases illustrated, the method gives results to within approximately ±10 percent for all relative concentration values $0 \leq C/C_0 \leq 1.0$ at time equal 360 days.

In addition, Figures 4-2 and 4-3 indicate that the results are stable for all times. Thus, the accuracy of the solution does not decrease with time. If the initial error which is introduced during the very early time steps when large concentration gradients are present can be minimized, then a high degree of accuracy can be maintained throughout the period of study.

## Verification of the Radial Convection Case

To show that the numerical model is applicable to problems other than simple one-dimensional flow, the model was run for a simplistic two-dimensional case. This involved simulating the injection of a contaminant into a confined aquifer through a recharge well. A constant rate of flow containing a conservative contaminant was injected into a homogeneous and isotropic confined aquifer and the convection of the contaminant was radially symmetric about the location of the well.

The model was first run for a square grid network where all grids were of a uniform size. The center grid of the system was used to simulate a recharge well by maintaining a constant head throughout the period of analysis. This resulted in radial, diverging flow into the aquifer from the recharge grid. The flow rate from the recharge grid into the aquifer remained constant for all time. The piezometric head of all grids surrounding the recharge grid were initially level and a uniform constant head was maintained on all boundary grids.

The concentration distribution curves for various times and the associated analytic solutions for Equation 2-13 neglecting dispersion are shown in Figure 4-4. It can be seen that the numerical solutions lag the analytic solutions by a large but relatively constant value. This can be attributed to the fact that the numerical model (using a rectangular coordinate system) is trying to simulate purely radial, diverging flow. The fact that the model only approximates this condition results in the errors shown.

In order to minimize this problem, a run was made for an almost identical hypothetical situation except the grid sizes were varied radially, from small dimensions near the recharge grid to larger grids on the edge of the grid network. The results for this condition are plotted in Figure 4-5. These results are better with regard to the location of the point where $C/C_0=0.5$, improving on the results shown in Figure 4-4.

Semi-logarithmic plots were made of piezometric head versus radial distance at time equal 270 days for both the uniform and variable grid size problems. While the results showed that neither solution was

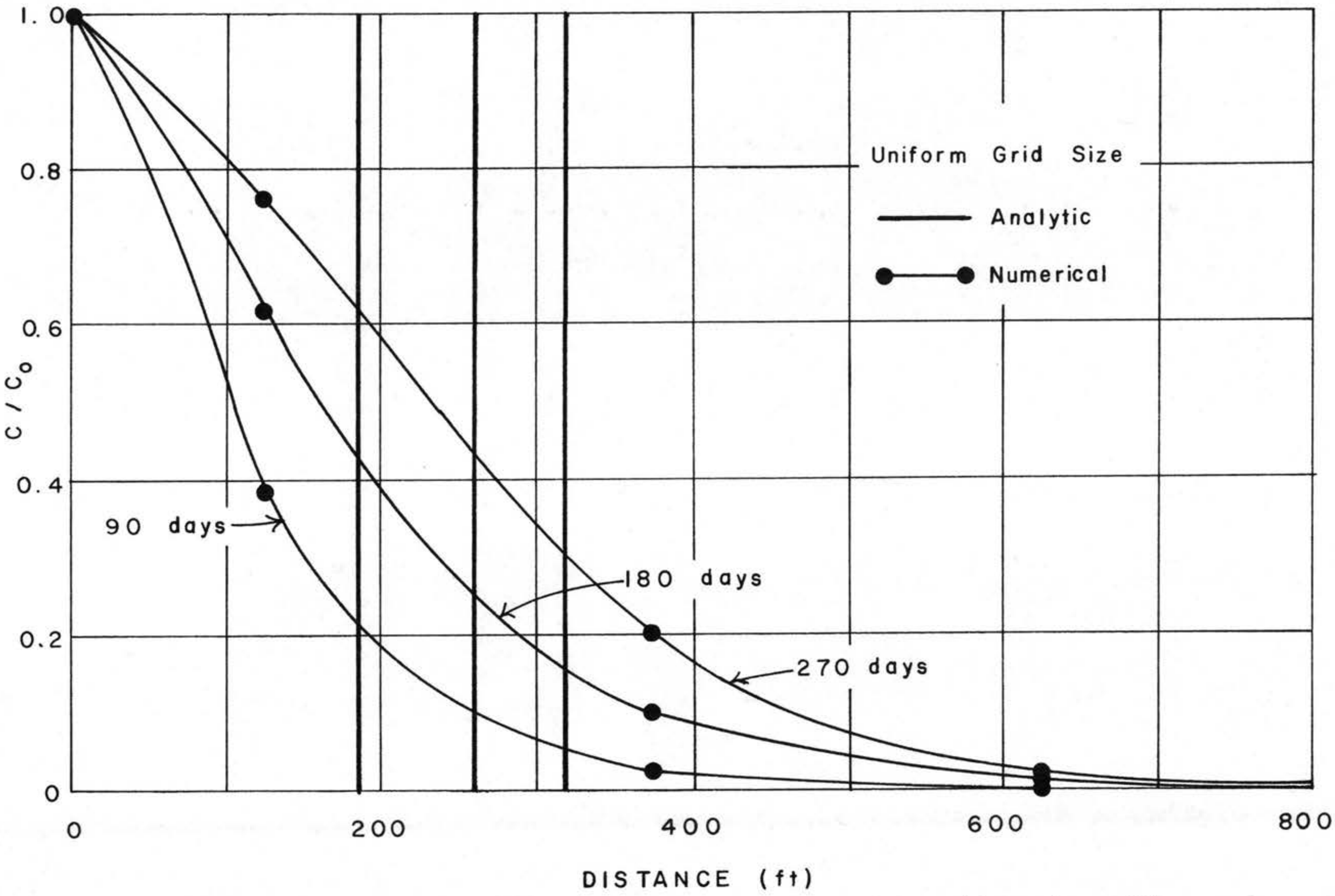


Figure 4-4. Concentration distribution curves for radial flow in a uniform size grid network.

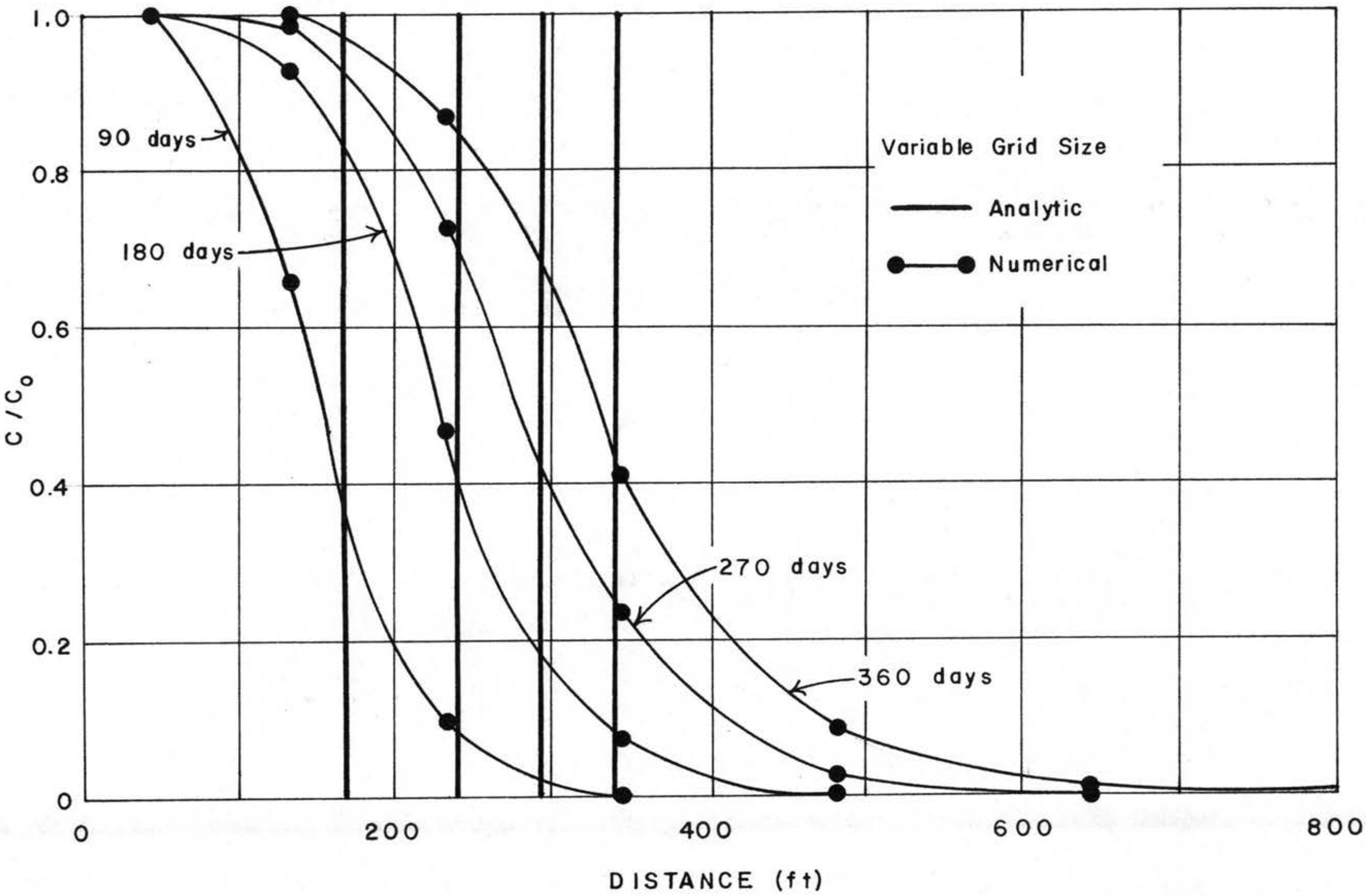


Figure 4-5. Concentration distribution curves for radial flow in a variable size grid network.

exact with regard to the radial flow case, both numerical solutions gave good approximations at points located away from the recharge grid. The curve for the variable grid size problem became linear at a radial distance of approximately 200 feet while the uniform grid size problem did not become linear until a radial distance of approximately 500 feet had been reached. The fact that the variable grid size problem gives a better approximation of the radial flow case nearer the recharge grid explains the reason for the improved accuracy over the uniform grid size problem.

The concentration distribution curves in Figures 4-4 and 4-5 exhibit significant amounts of numerical dispersion. As time increases the magnitude of the numerical dispersion increases. However, the error in distance between the numerical and analytic solutions at the point where $C/C_0=0.5$ remains constant with increasing time.

For radially symmetric, diverging flow with a constant flow rate, the velocity of the fluid decreases with increasing distance from the recharge grid. It will be shown in Chapter V that the degree of numerical dispersion is a function of the grid size, time increment and seepage velocity.

## Stability Criteria

The general equation governing longitudinal convection and dispersion, which was discussed previously, is

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} \tag{2-2}$$

For the purpose of developing the simplistic model, the term $D_L\frac{\partial^2 C}{\partial x^2}$ was assumed to be zero. This reduced Equation 2-2 to

$$\frac{\partial C}{\partial t} = - v\frac{\partial C}{\partial x} \tag{4-1}$$

Using the backward finite difference expansion, Equation 4-1 becomes

$$\frac{C_i^t - C_i^{t+\Delta t}}{\Delta t} = - v \frac{C_i^t - C_{i-1}^t}{\Delta x} \qquad (4\text{-}2)$$

Rearranging Equation 4-2 and solving for $C_i^{t+\Delta t}$ yields

$$C_i^{t+\Delta t} = \frac{v \cdot \Delta t}{\Delta x} [C_{i-1}^t - C_i^t] + C_i^t \qquad (4\text{-}3)$$

Noting that contaminant concentrations are at all times between zero and one, and that the worst condition is given by $C_i^t=0$, $C_{i-1}^t=1.0$ and $C_{i-1}^{t+\Delta t}=1.0$, Equation 4-3 reduces to

$$1 = \frac{v \cdot \Delta t}{\Delta x} [1 - 0] + 0 \qquad (4\text{-}4)$$

Simplifying this equation leads to the stability criteria

$$\frac{\Delta x}{v \cdot \Delta t} \geq 1.0 \qquad (4\text{-}5)$$

An identical criteria was developed empirically and is discussed below.

Upon examining the runs made using the numerical model, it was noted that the volume of water flowing through a finite difference grid during each time increment must not exceed the volume of water stored in the grid during the time increment under study or severe oscillation and instability of the solution would occur. Mathematically, this necessary condition for the one-dimensional flow case may be expressed as

$$Q \leq \Delta x \cdot \Delta y \cdot h \cdot \phi \qquad (4\text{-}6)$$

where $Q$ = volume of flow through the grid

$\Delta x$, $\Delta y$ = grid dimensions

$h$ = saturated thickness

$\phi$ = porosity.

Noting that the volume of flow through the grid may be expressed using Darcy's law, the grid dimensions and the time increment, Equation 4-6 may also be written as

$$v \cdot \Delta y \cdot \Delta t \cdot h \cdot \phi \leq \Delta x \cdot \Delta y \cdot h \cdot \phi \tag{4-7}$$

where $v$ is the seepage velocity and $\Delta t$ is the time increment. Cancelling like terms and rearranging this equation, we get

$$\frac{\Delta x}{v \cdot \Delta t} \geq 1.0 \tag{4-8}$$

This relationship (which is identical to that developed by expanding the governing partial differential equation) indicates that the grid dimension in the direction of flow must at all times be greater than or equal to the seepage velocity times the time increment. If this criteria is not met, severe oscillations and instability, as shown in Figures 4-6 and 4-7, will occur. It can also be shown that the greates accuracy of the model occurs when $\frac{\Delta x}{v \cdot \Delta t} = 1.0$. Figures 4-2 and 4-3, discussed earlier, are plots of two specific instances where this stability criteria has a value of unity.

<u>Conservation of Contaminant Mass</u>

Contaminant mass within the groundwater system is conserved at all times. This is a result of using the fully explicit method to calculate relative contaminant concentrations (i.e. mass of contaminant within each

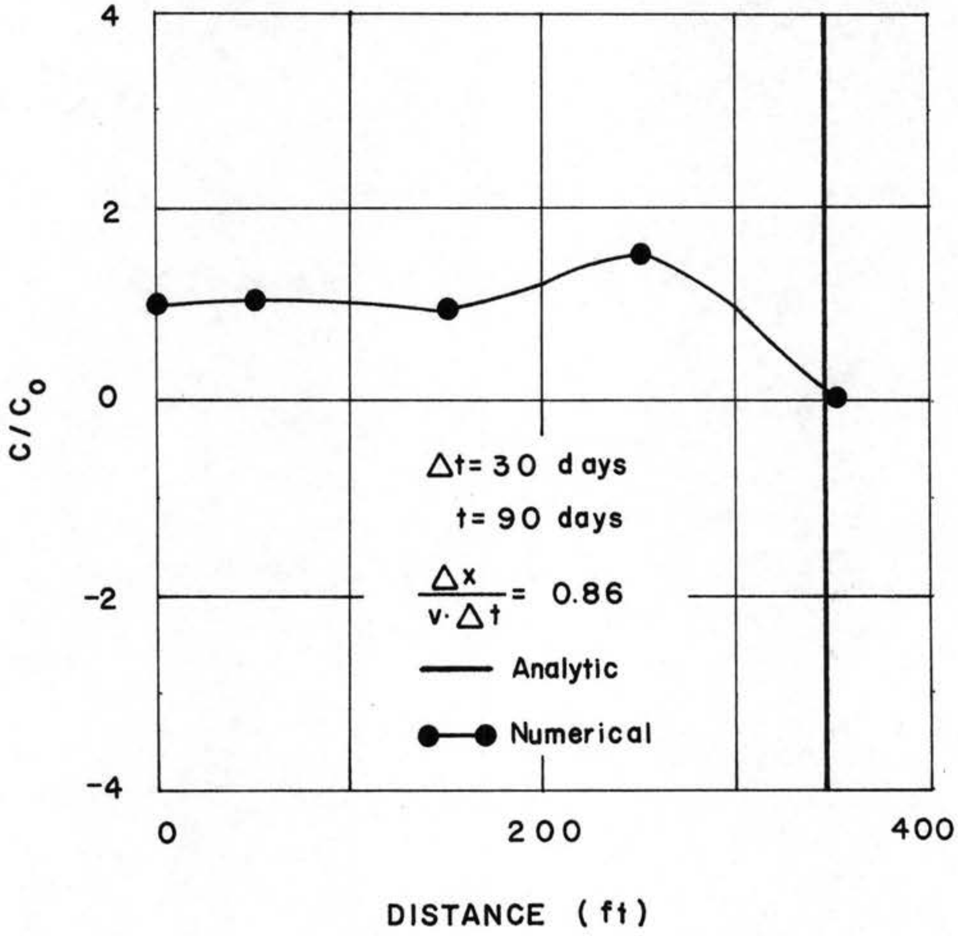


Figure 4-6. Oscillation of numerical solution for $\frac{\Delta x}{v \cdot \Delta t} = 0.86$ after 90 days.

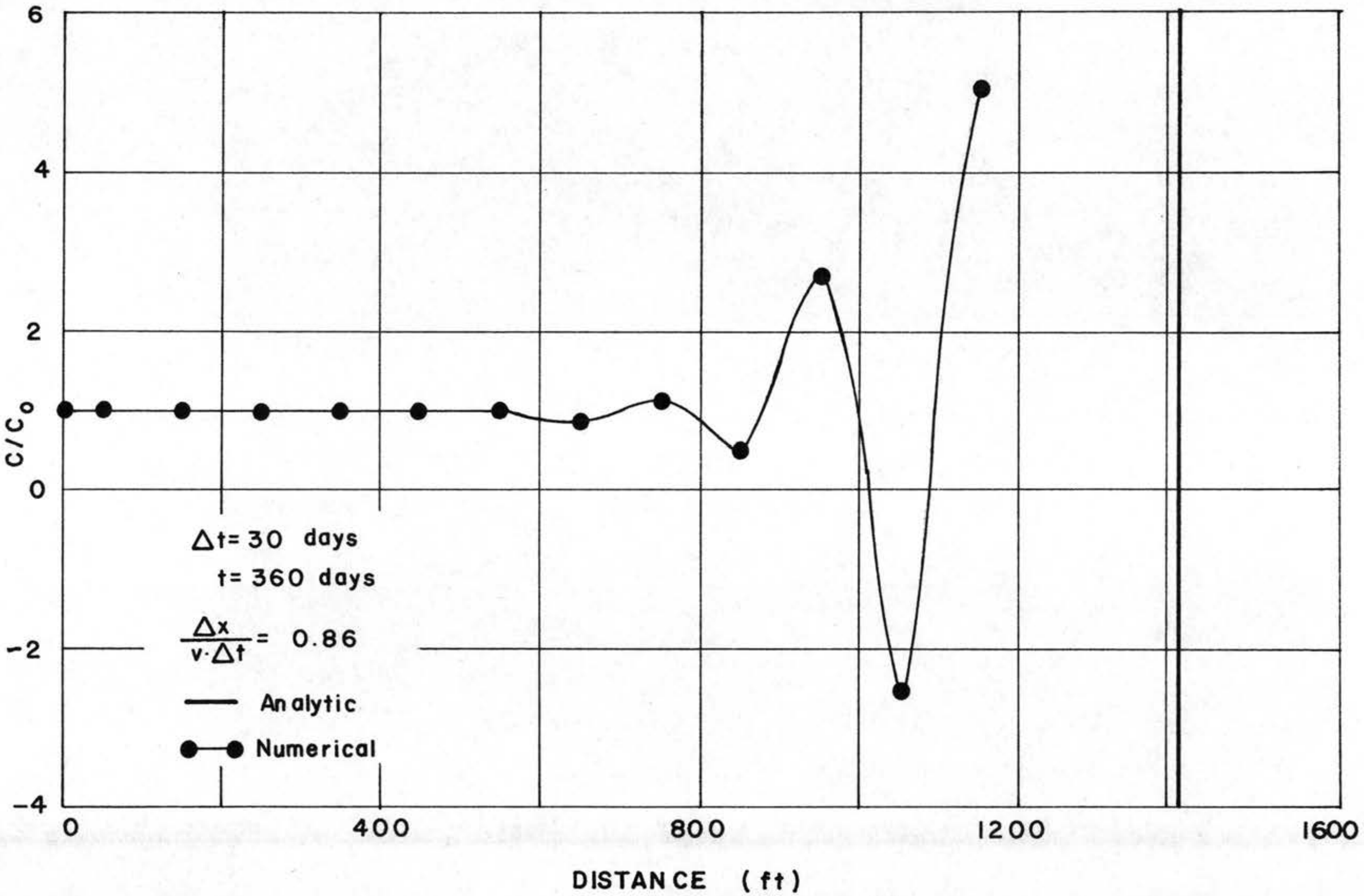


Figure 4-7. Oscillation of numerical solution for $\frac{\Delta x}{v \cdot \Delta t} = 0.86$ after 360 days.

grid). Chapter III contains a detailed discussion of the concentration calculation process.

All $C/C_0$ values range between 0.0 and 1.0. Since concentrations beyond the third significant figure are not normally of interest, the model only prints out concentrations to three decimal places. Many computers carry numbers to 10 or 15 significant figures. Therefore, grids with a printed concentration of 0.000 often have small contaminant concentrations. In order for a total conservation of contaminant mass to occur, these small concentrations must always be taken into account.

# CHAPTER V

## SENSITIVITY ANALYSIS OF THE NUMERICAL MODEL

The response behavior of the groundwater system to the convection of a contaminant may be influenced by many input variables and the interaction of many system parameters. The number of possible combinations of these factors is infinite -- not only in terms of magnitude of the factors, but also variations in time and space. It is seldom economically feasible to quantitatively evaluate all or most of the input variables and system parameters with precision. It is, however, very important that the effect of these variables on the accuracy of the model be known.

While most aquifers are not homogeneous and isotropic, these basic assumptions were made in order to simplify the development of the numerical model. As such, sensitivity of the numerical model to variations in the aquifer properties (i.e., permeability, stratification, porosity, storage coefficient, etc.) will not be discussed here. The parameters grid size, time increment and seepage velocity are the primary components of the stability criteria. The effects of these properties on the accuracy of the numerical model should be studied prior to the effects of the aquifer properties.

Grid Size

For the purpose of analyzing the model's sensitivity to grid size, time increments of 10, 30 and 45 days were chosen. Previous work with the basic groundwater flow model indicated that these time increments yield results of sufficient accuracy for the groundwater flow. Also, a total model time of 360 days was chosen to compare the results of the various grid sizes.

Figure 5-1 shows the concentration distribution curves for grid sizes 115, 300, 500 and 1000 feet when the time increment is 30 days. It can be seen that the numerical dispersion increases with increasing grid size. As grid size increases, the numerical solution, as evidenced by the point where $C/C_0=0.5$, lags the analytic solution by an increasing amount. However, the calculated distance where $C/C_0=0.5$ for the 1000 foot grid size only lags the analytic solution by approximately 10 percent. Table 5-1 illustrates the percent error of distance for each grid size at various $C/C_0$ values.

TABLE 5-1. Value of $C/C_0$ Versus Percent Error in Calculated Distance

| $C/C_0$ | PERCENT DISTANCE ERROR | | | |
|---|---|---|---|---|
| | 115' | 300' | 500' | 1000 |
| 0 | 3.6 | 82.9 | | |
| 0.2 | 1.4 | 30.2 | | |
| 0.4 | 0 | 7.2 | | |
| 0.5 | 0 | - 1.4 | -3.6 | -11.0 |
| 0.6 | 0 | - 9.3 | | |
| 0.8 | - 1.4 | - 31.0 | | |
| 1.0 | -11.5 | -100.0 | | |

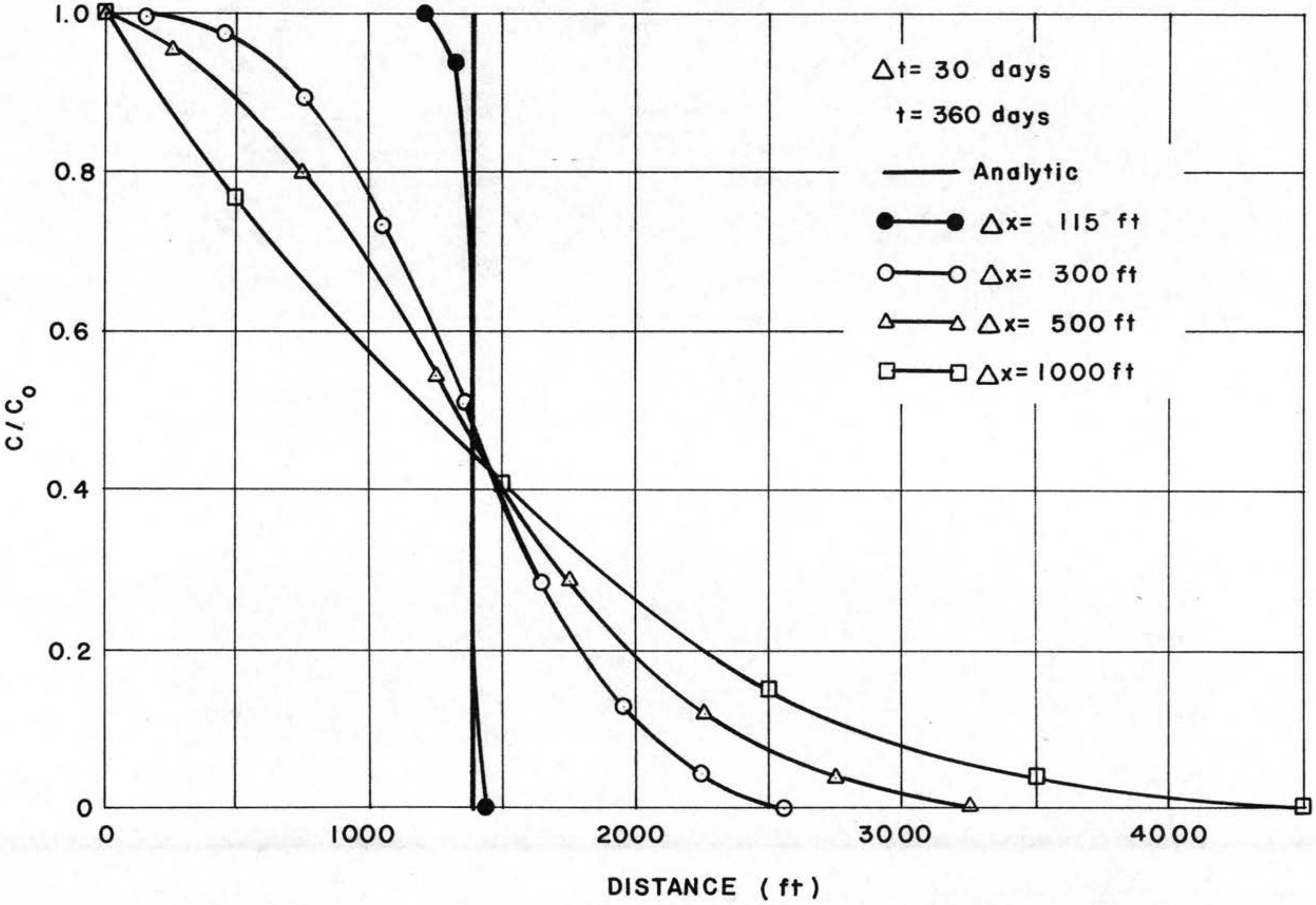


Figure 5-1. Concentration distribution curves for various grid sizes with $\Delta t$=30 days.

The data in Table 5-1 indicates that if a value of $\frac{\Delta x}{v \cdot \Delta t} = 1$ is chosen (in this instance this corresponds to a grid size of 115 feet), then accuracy within ±10 percent can be obtained for the entire concentration distribution curve while accuracy to within ±2% can be obtained for all values $0.2 \leq C/C_0 \leq 0.8$. Thus, the model has the capability of giving very accurate results. For $\frac{\Delta x}{v \cdot \Delta t} = 2.6$ (a grid size of 300 feet), accuracy to less than ±10 percent can be obtained for all values $0.4 \leq C/C_0 \leq 0.6$. As grid size increases, the model does lose accuracy. Yet, very good results are obtained for the location of the point where $C/C_0 = 0.5$ for all grid sizes. Figures 5-2 and 5-3 show the concentration distribution curves for various grid sizes when the time increment equals 10 days and 45 days, respectively. These figures confirm the conclusions drawn with respect to the 30 day time increment.

The data for grid sizes 115 feet and 300 feet in Table 5-1 also indicate that the numerical model does not produce a symmetric numerical dispersion pattern. This can be attributed to the fully explicit mass balance technique which is used to calculate the relative contaminant concentrations. Regardless of the speed at which the contaminant front moves, the numerical model advances the contaminant concentrations one grid with each calculation. As the time of analysis increases, so does the numerical dispersion and non-symmetry of the concentration distribution curve. Figures 5-1, 5-2, and 5-3 all indicate this pattern. However, by keeping the value of $\frac{\Delta x}{v \cdot \Delta t}$ as close to 1.0 as possible, this numerical dispersion and non-symmetric pattern is kept at a minimum, and in the case where $\frac{\Delta x}{v \cdot \Delta t} = 1$ actually stabilizes.

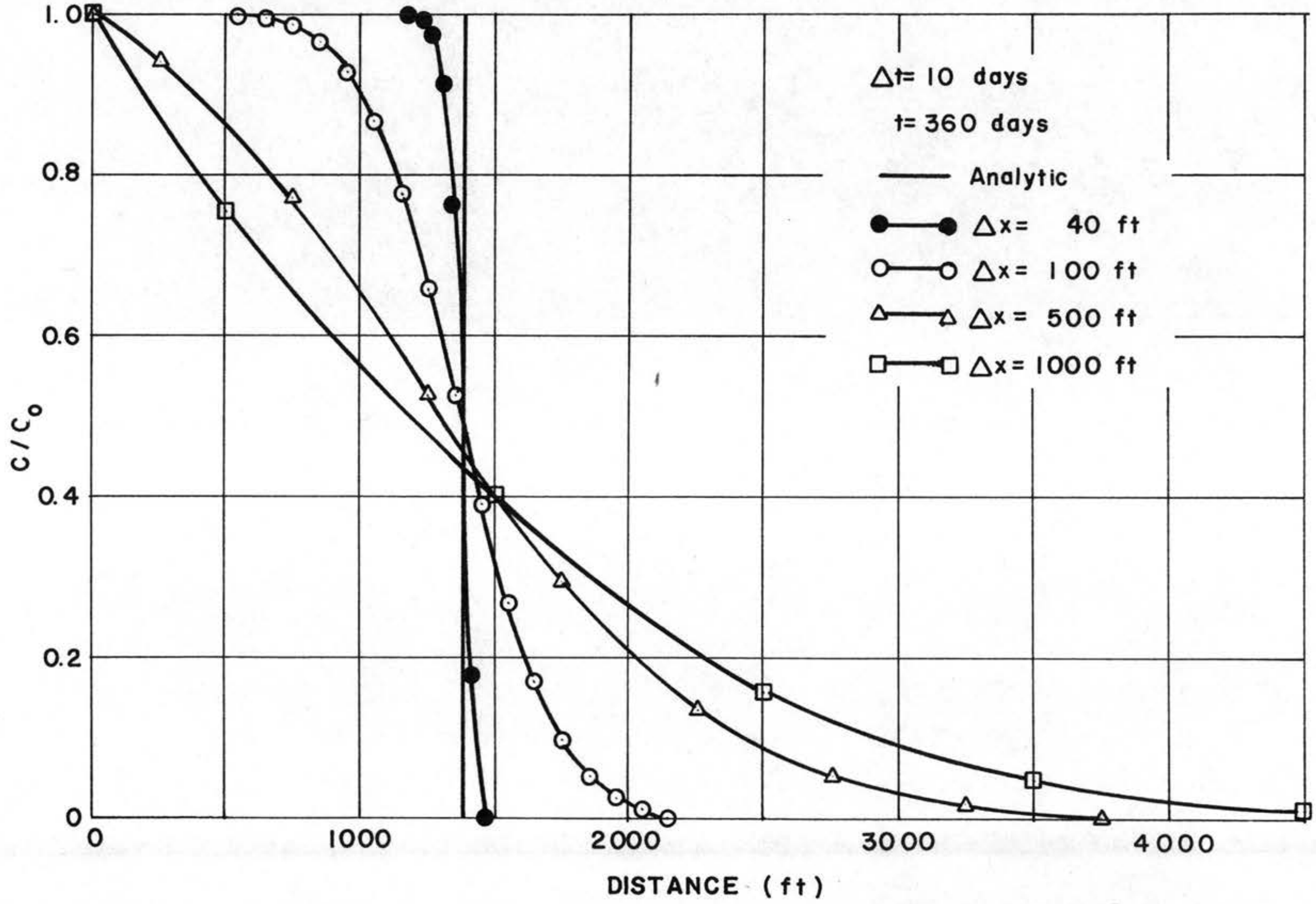


Figure 5-2. Concentration distribution curves for various grid sizes with $\Delta t$=10 days.

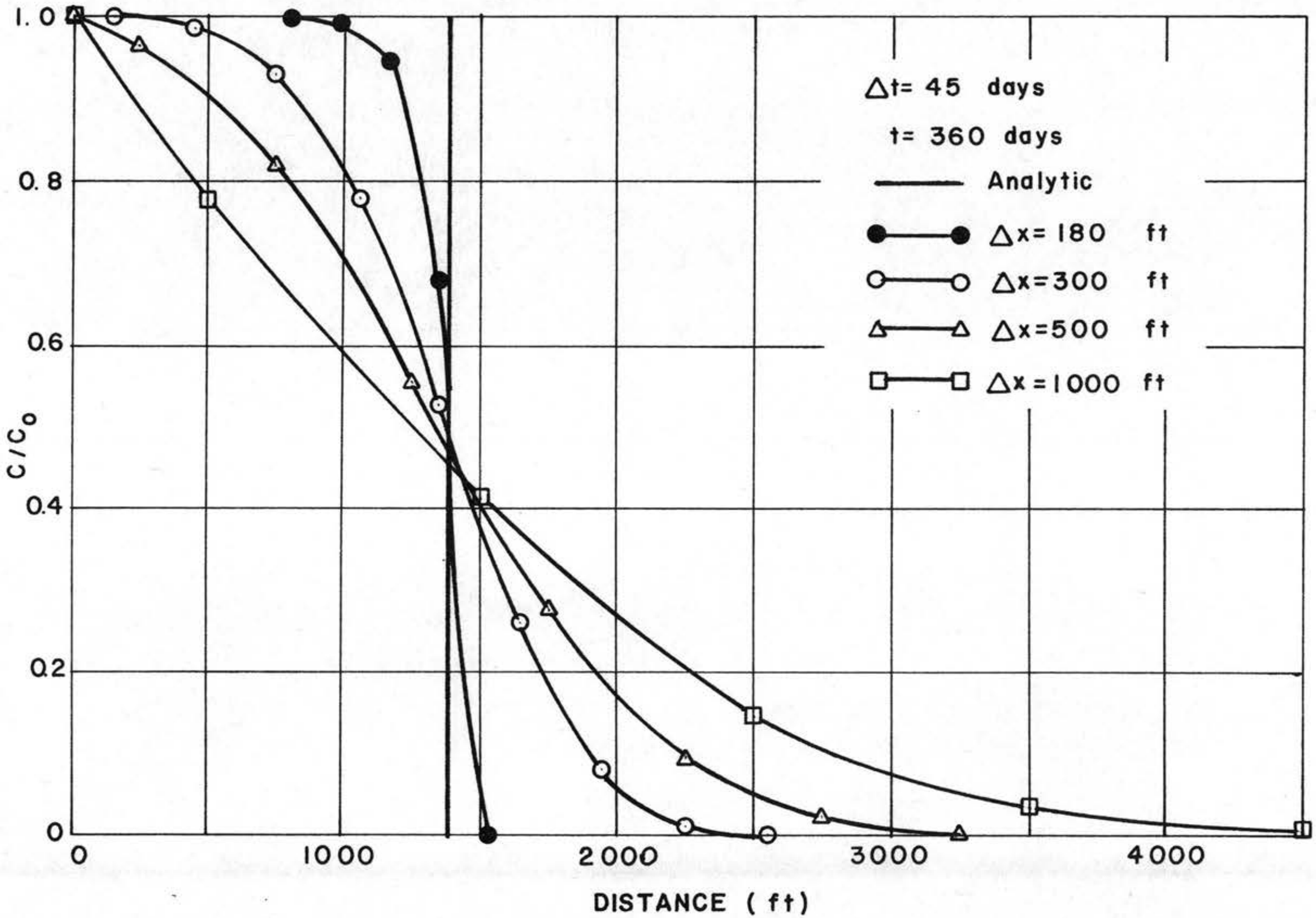


Figure 5-3. Concentration distribution curves for various grid sizes with Δt=45 days.

Time Increment

Figure 5-4 shows the relationship of the concentration distribution curves for time increments of 10, 30 and 45 days with a constant grid size of 300 feet at time equal 360 days. This illustrates that the use of a small time increment actually leads to an increase in numerical dispersion. This is due to the use of the fully explicit mass balance technique to calculate the relative concentration values. If a time increment of 10 days is used, three calculations are made over a thirty-day period as opposed to one for a thirty-day time increment. Since each calculation moves the contaminant down-gradient one grid, the model has a tendency to smear the front with each mass balance calculation. The use of as large a time increment as possible while meeting the stability criteria will keep this numerical smear to a minimum.

From Figure 5-4, it can be seen that each time increment gives approximately the same distance for a $C/C_0$ value of 0.5. Therefore, it can be concluded that while the time increment does have some effect on the accuracy of the numerical model, the effect is not as severe as that caused by variation in grid size.

The maximum value which can be chosen will be dictated by the hydrologic accuracy of the numerical model and the stability criteria. Figures 5-5 and 5-6 show the concentration distribution curves for various times when the grid size equals 500 feet and 115 feet, respectively. These figures confirm the conclusions drawn with respect to the 300 foot grid size. It should be noted that the larger variation

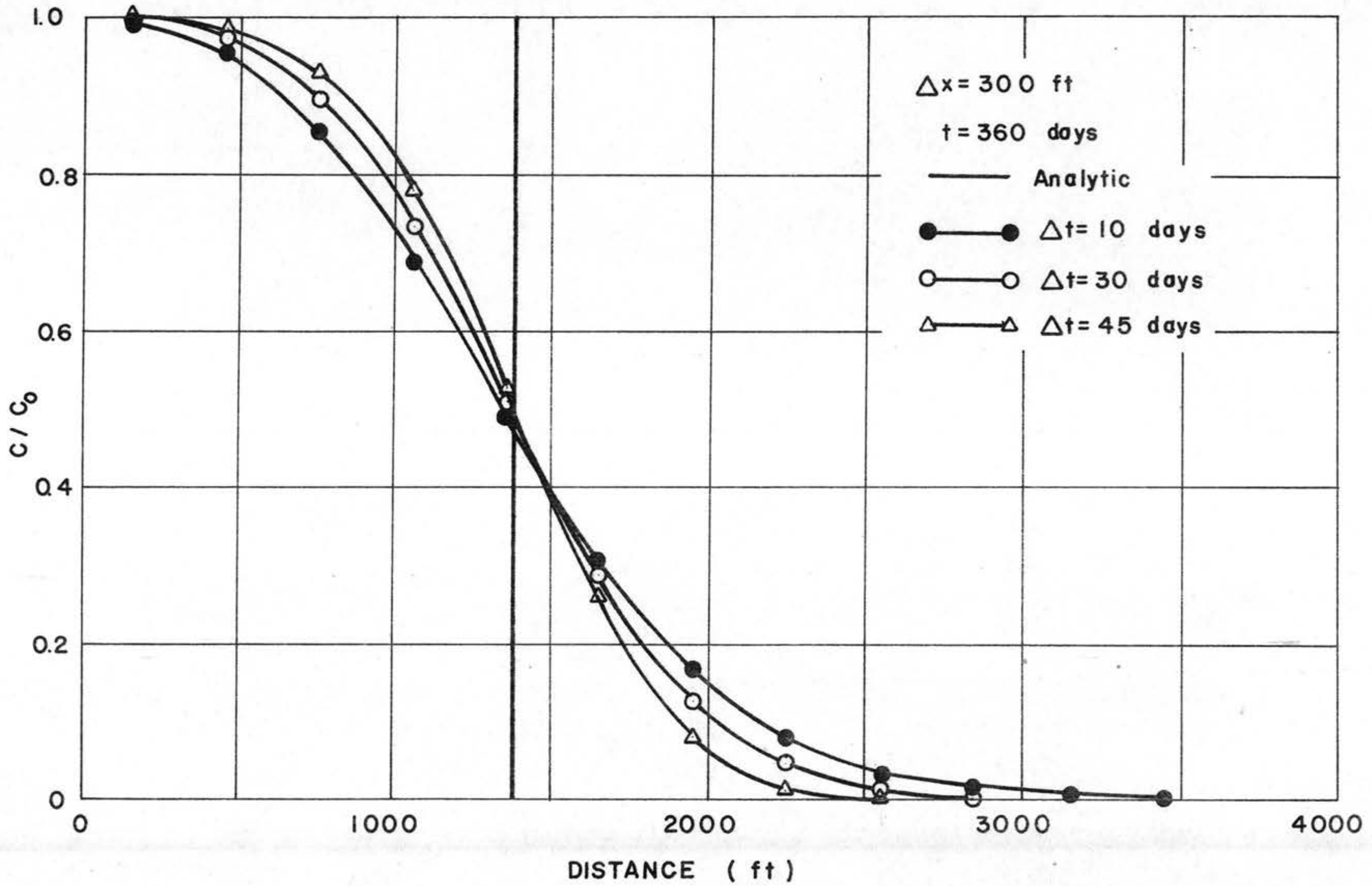


Figure 5-4. Concentration distribution curves for various time increments with Δx=300 feet.

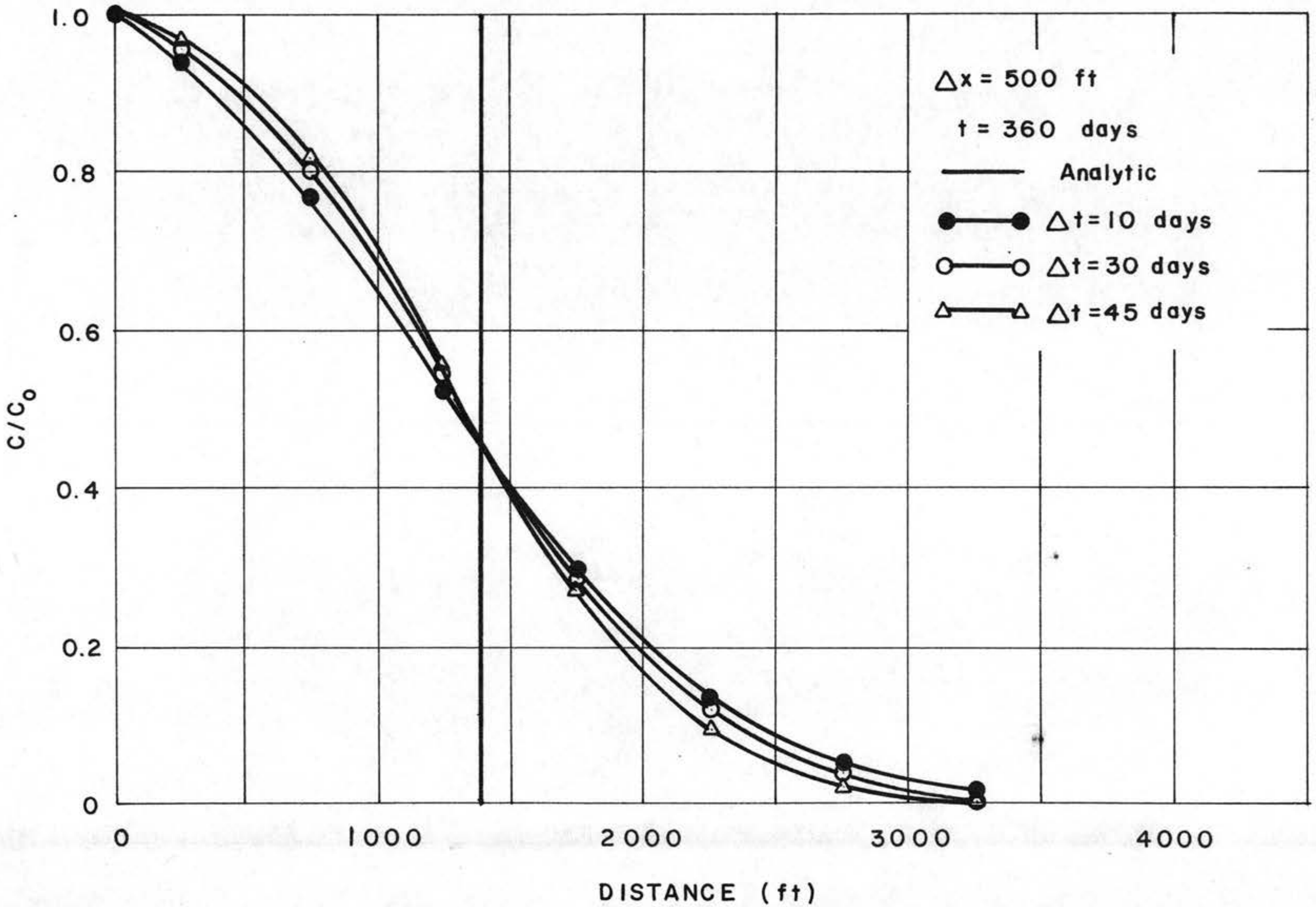


Figure 5-5. Concentration distribution curves for various time increments with Δx=500 feet.

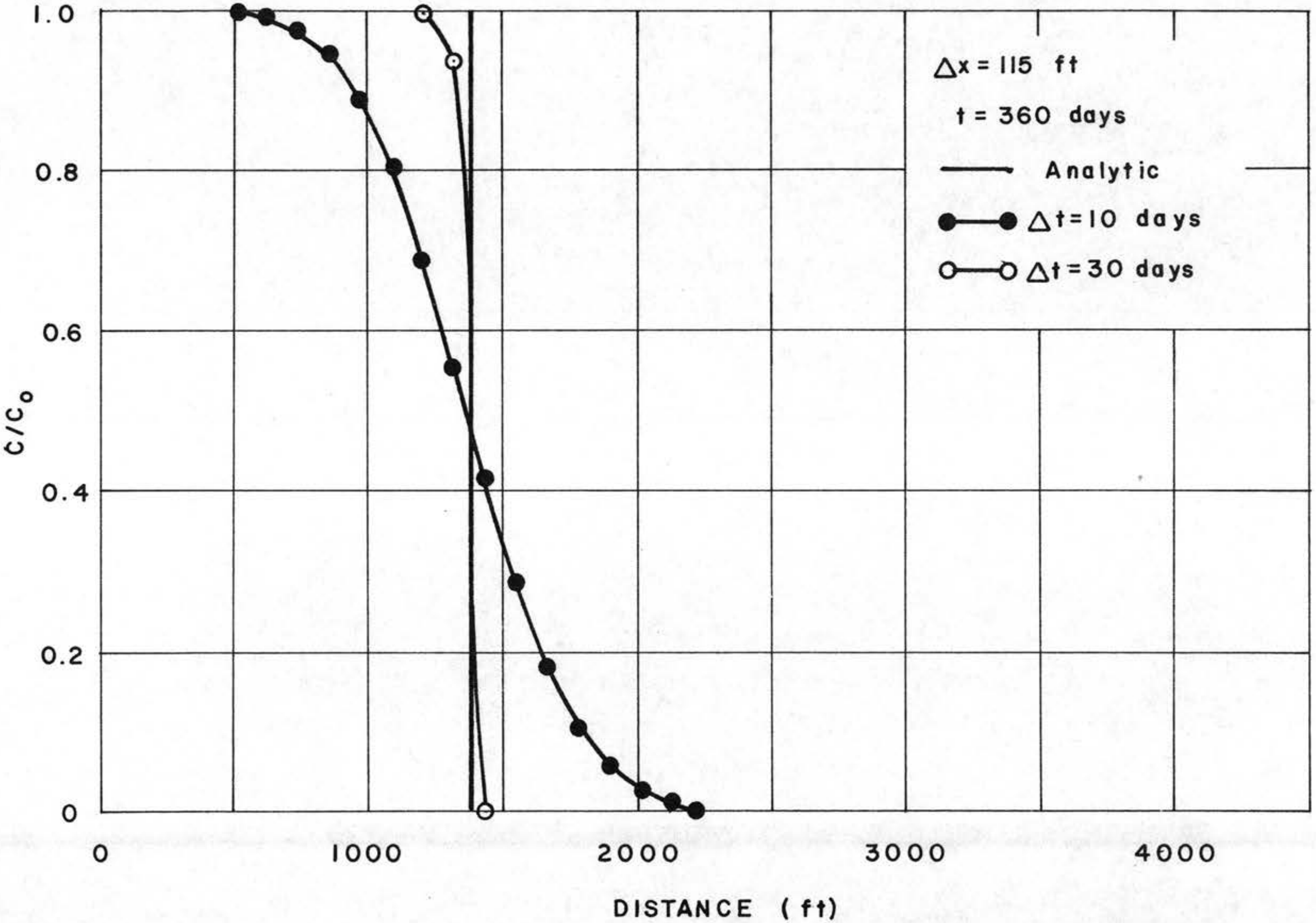


Figure 5-6. Concentration distribution curves for various time increments with Δx=115 feet.

indicated by Figure 5-6 is due to the fact that the $\frac{\Delta x}{v \cdot \Delta t}$ value for the 30 day time increment is 1.0, resulting in a very accurate approximation to the analytic solution which somewhat distorts the comparison with the 10 day time increment.

Seepage Velocity

As indicated by Equation 2-16, the dispersion coefficient is directly related to the seepage velocity. The analytic results presented previously are all related to one hypothetical case where the coefficient of longitudinal dispersion was calculated to be $1.44 \times 10^{-3}$ $ft^2$/day. It should be noted that the coefficient of dispersion was estimated based on Equation 2-16 (Harleman, et al, 1963). While there is a small loss of accuracy in estimating the coefficient in this manner, the research by Harleman, et al, indicated that this is a valid relationship which gives accurate results. The results of this study tend to indicate that this estimation is very accurate and that confidence can be expressed in the results obtained based upon this empirical relationship.

To verify the validity of the numerical model for general use, the model was run for hypothetical cases using various values of seepage velocity. Table 5-2 lists the particular cases studied. As with the original hypothetical case, McWhorter and Sunada (1977) was used as a reference to obtain typical values of porosity and hydraulic conductivity for groundwater aquifers.

The concentration distribution curves for the medium sand and medium gravel are shown in Figures 5-7 and 5-8, respectively. It is apparent that the numerical model is valid for these different values of the seepage velocity and the associated dispersion coefficients. As discussed in the previous section, when $\frac{\Delta x}{v \cdot \Delta t}=1$ the numerical model produces a close approximation to the analytic solution. As the value of $\frac{\Delta x}{v \cdot \Delta t}$ increases, numerical dispersion increases. However, the model continues to produce accurate results with respect to the location of the point where $C/C_0=0.5$ for all values of the seepage velocity. From this analysis, it can be concluded that while the numerical model neglects the dispersion process, the effect of dispersion for typical aquifer properties is very small relative to convection over the time periods used and thus the model is valid for the range of seepage velocities studied.

TABLE 5-2. Data for Cases Tested

| CASE | TYPE OF MATERIAL | POROSITY $\phi$ | HYDRAULIC CONDUCTIVITY K ft/day | SEEPAGE VELOCITY v ft/day | DISPERSION COEFFICIENT $D_L$ $ft^2/day$ |
|---|---|---|---|---|---|
| 1 | Medium Sand | 0.41 | 40 | 0.975 | $1.26 \times 10^{-4}$ |
| 2 | Coarse Sand | 0.39 | 150 | 3.846 | $1.44 \times 10^{-3}$ |
| 3 | Medium Gravel | 0.31 | 1140 | 36.84 | $7.32 \times 10^{-2}$ |

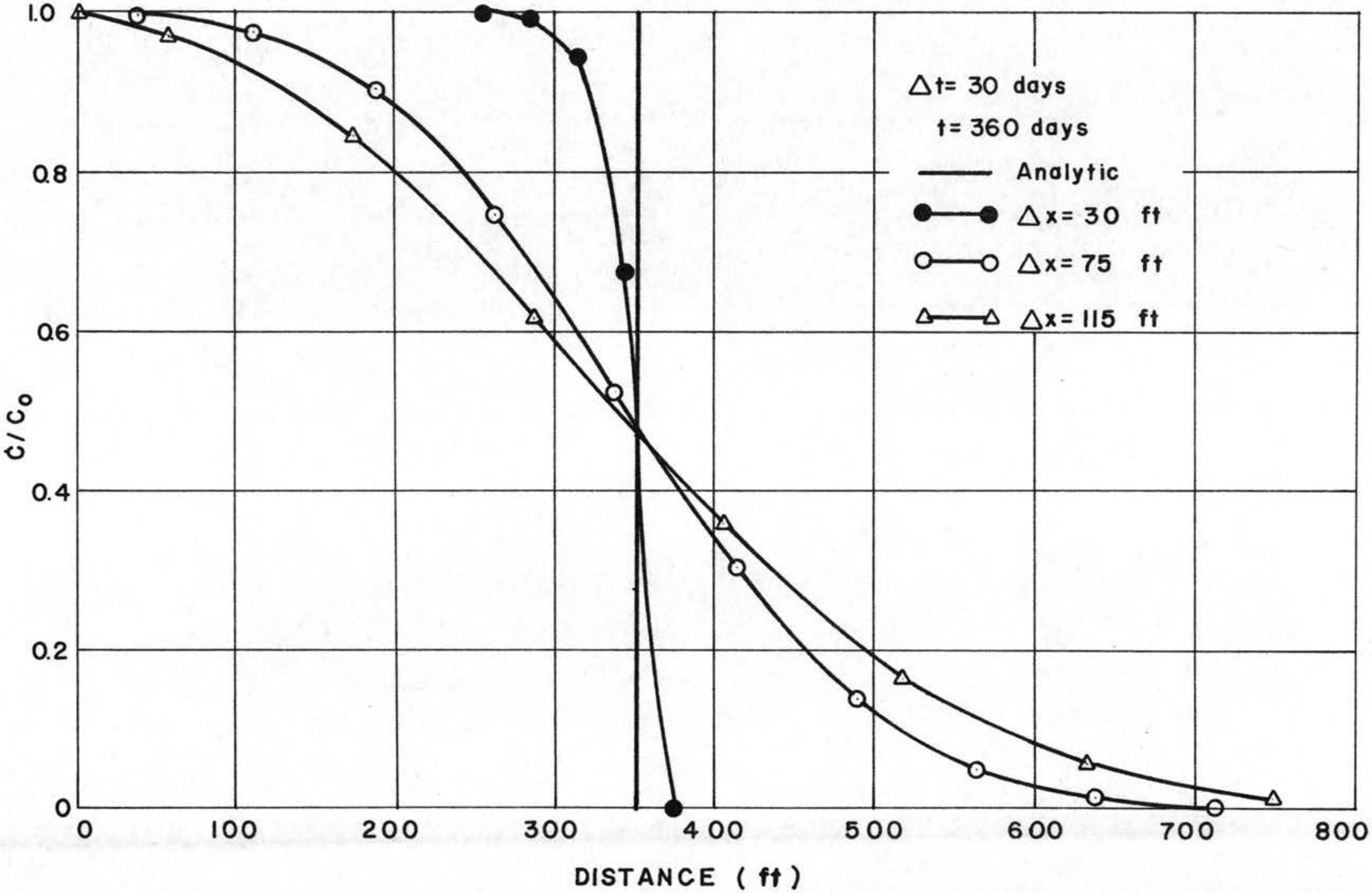


Figure 5-7. Concentration distribution curves for a medium sand.

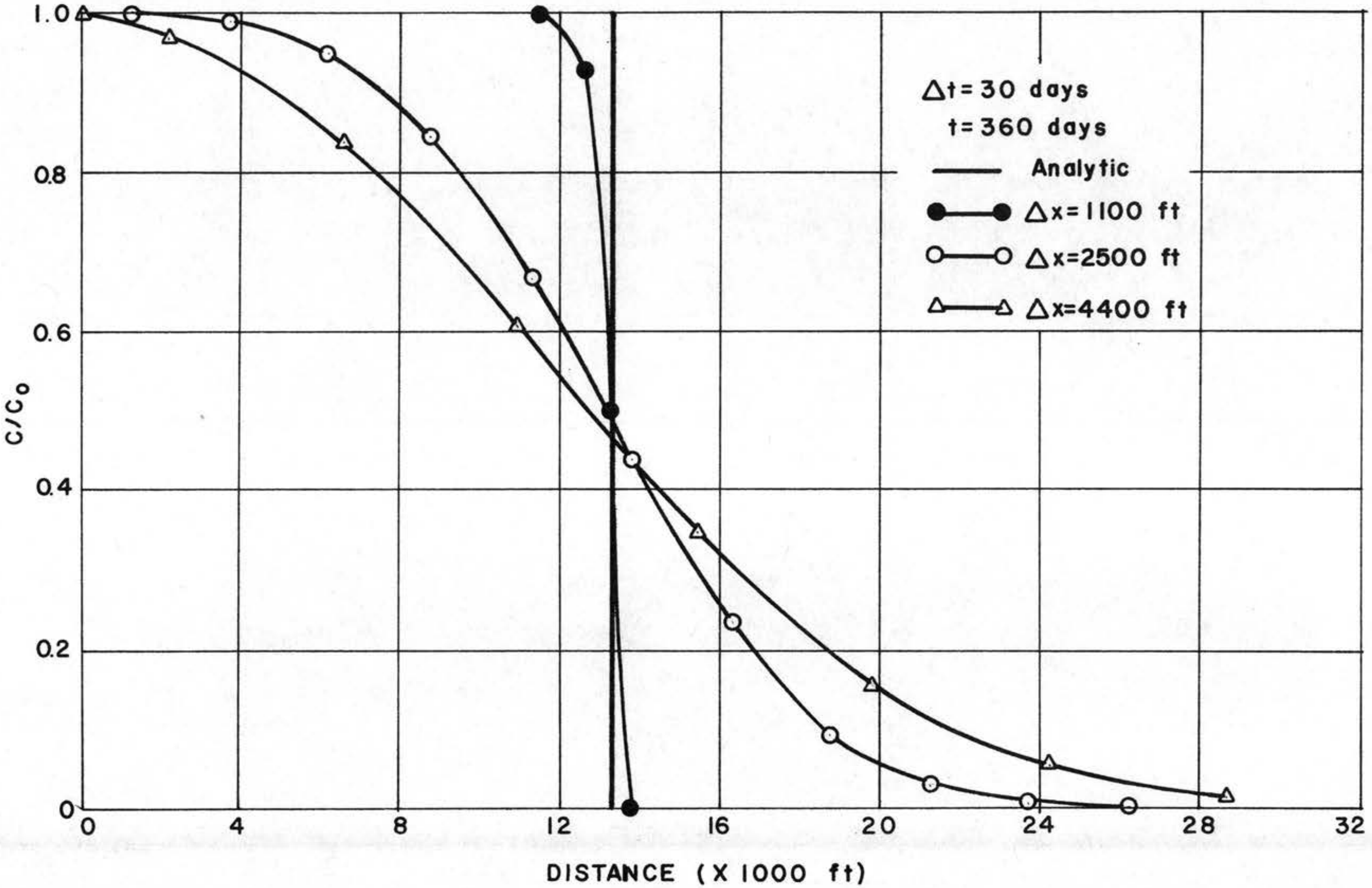


Figure 5-8. Concentration distribution curves for a medium gravel.

Summary of the Sensitivity Analysis

Results of the sensitivity analysis produce three independent conclusions. First, the grid size has a very large effect on the accuracy of the numerical model. For a constant time increment, the larger the grid size, the larger the numerical dispersion. Second, the value of the time increment chosen has little effect on the accuracy of the model. However, the larger the time increment, the greater the accuracy. Finally, the model is valid for a relatively wide range of seepage velocities commonly encountered in groundwater systems.

Collectively, additional conclusions can be drawn. Since the best numerical solutions occur when $\frac{\Delta x}{v \cdot \Delta t} = 1$ and when large time increments are used, this forces the use of large grid sizes which reduce computer time and storage requirements. So long as the value of $\frac{\Delta x}{v \cdot \Delta t}$ remains close to 1.0, the use of larger grid sizes does not significantly effect the accuracy of the model. In addition, the accuracy of the model for cases where $\frac{\Delta x}{v \cdot \Delta t} = 1$ is so good that results for all values $0 \leq C/C_0 \leq 1$ can be used with confidence. However, as the value of $\frac{\Delta x}{v \cdot \Delta t}$ increases, the range over which the $C/C_0$ values are acceptible decreases. Regardless, for all grid sizes the model produces very accurate locations of the point where $C/C_0 = 0.5$.

## CHAPTER VI

## CONCLUSIONS AND RECOMMENDATIONS

From the results of this study, it can be concluded that the numerical model is a valid numerical approach for simulating convection in confined groundwater aquifers. The accuracy of the model is strongly dependent on the value of the function $\frac{\Delta x}{v \cdot \Delta t}$. If the value of this function can be maintained near unity, very good accuracy of the dispersion process can be obtained. While larger values of the function result in increasing amounts of numerical dispersion, the model at all times locates the point where $C/C_0=0.5$ with good accuracy.

With regard to the sensitivity of the model, conclusions can be drawn about each of the terms which appear in the function $\frac{\Delta x}{v \cdot \Delta t}$. With $v$ and $\Delta t$ held constant, increased numerical dispersion results with larger grid sizes. With $\Delta x$ and $v$ held constant, varying $\Delta t$ has a much smaller effect on model accuracy than varying $\Delta x$. However, as $\Delta t$ is increased, numerical dispersion is minimized and the accuracy of the model increases. The model is valid for a wide range of seepage velocities subject to the limitations imposed by varying $\Delta x$ and $\Delta t$. It is shown that, for a given seepage velocity, the best results are obtained by maximizing $\Delta t$ within the limits of the accuracy of the groundwater flow portion of the model and minimizing $\Delta x$ so that the value of $\frac{\Delta t}{v \cdot \Delta t}$ approaches 1.0. While this criteria does somewhat limit grid size, grid sizes on the order of hundreds of feet should be possible for most cases.

While the majority of work done as a part of this study was based on the one-dimensional, steady state flow condition, the model was developed to simulate two-dimensional, areal distribution of contaminants. For the radially symetric, diverging flow situation, the model produced relatively good results as the numerical approximation of the groundwater flow equation approached the solution for pure radial flow. The numerical dispersion increased with increasing distance from the contaminant source and is attributable to the increase in the value of the function $\frac{\Delta x}{v \cdot \Delta t}$ as the radial distance increases.

Several runs were made in which various numbers of recharge pits, pumping wells, constant head sources and phreatophyte sources were used. These indicated that the programming modifications made are correct insofar as computer language is concerned. However, no hypothetical cases were run to determine the accuracy and sensitivity of these contaminant sources.

In general, the numerical model minimizes many of the problems encountered with the development of previous numerical models. The model does not require prohibitive amounts of computer time or storage. It has the capability of handling impermeable, constant head and constant gradient boundaries. When the stability criteria is followed, the model is stable and converges to a reasonably accurate solution.

It is recommended that the following areas be studied with regard to the fully explicit mass balance approach of simulating convection in groundwater aquifers:

1. The validity of the model should be verified for non-homogeneous confined aquifers.
2. The validity of the model for both homogeneous and non-homogeneous unconfined aquifers should be established.
3. The model should be applied to an actual field problem.

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# APPENDIX A

# DETERMINATION OF HYPOTHETICAL AQUIFER PROPERTIES

# APPENDIX A

## DETERMINATION OF HYPOTHETICAL AQUIFER PROPERTIES

In order to show that WTQUAL2 is a valid dispersion simulator, it was felt that the data used in the comparison of the analytic and numerical solutions should be representative of values commonly encountered in actual physical situations. Therefore, typical values of hydraulic conductivity and porosity were chosen from a table in McWhorter and Sunada (1977) containing maximum, minimum and arithmetic mean values for soils ranging from the finest silts and clays to coarse gravels. The values $K=150$ ft/day and $\phi=0.39$ were chosen for the sensitivity analysis of grid size and time increment and are representative of a typical coarse sand.

Once these values were chosen, it was then necessary to choose a value for the hydraulic gradient. Review of several actual physical situations indicated that a gradient of 0.01 (10 feet change in vertical elevation per 1000 feet change in horizontal distance) is typical and so this value was chosen.

Assuming that the flow regime would be laminar (this will be checked later), Darcy's law was applied. The version used in this situation was

$$q = K \cdot \frac{dh}{dl} \qquad \text{(A-1)}$$

where $q$ is the Darcy velocity, $K$ is hydraulic conductivity, and $\frac{dh}{dl}$ is the hydraulic gradient. Using the previously chosen values for $K$ and $\frac{dh}{dl}$, a Darcy velocity $q$ of 1.50 ft/day was obtained. Dividing this value by the porosity gave a seepage velocity $v$ of 3.846 ft/day.

At this point in the analysis an additional assumption had to be made. For the purpose of this study, a groundwater temperature of 50°F was chosen. The groundwater system was then assumed to be isothermal throughout the period of study. The appropriate fluid properties of water at this temperature are

| | |
|---|---|
| dynamic viscosity | $\mu = 2.735 \times 10^{-5}$ lb-sec/ft$^2$ |
| kinematic viscosity | $\nu = 1.410 \times 10^{-5}$ ft$^2$/sec |
| density | $\rho = 1.94$ slugs/ft$^3$ |
| acceleration of gravity | $g = 32.2$ ft/sec$^2$ |
| specific weight | $\gamma = 62.4$ lb/ft$^3$. |

Applying the relationship between hydraulic conductivity and intrinsic permeability $k$

$$k = \frac{K \cdot \mu}{\rho\, g} = \frac{K \cdot \mu}{\gamma} \tag{A-2}$$

yielded a permeability of $7.609 \times 10^{-10}$ ft$^2$.

At this point, Equation 2-16 as developed by Harleman et al (1963) was applied and a longitudinal dispersion coefficient value $D_L = 1.439 \times 10^{-3}$ ft$^2$/day was obtained. This value was then used in Equation 2-5 to obtain the analytic solution values of the concentration distribution curve.

To verify that the flow regime was laminar, the Reynold's number $\mathbb{R}$ was calculated from the following equation:

$$\mathbb{R} = \frac{v\sqrt{k}}{\nu} \tag{A-3}$$

This calculation yielded $\mathbb{R} = 8.708 \times 10^{-5}$. Since this value is less than 0.01, the flow regime can be characterized as laminar and Darcy's law applies.

To determine the storage coefficient, it was necessary to estimate values for the pore volume compressibility and the compressibility of water due to the formation lying above the confined aquifer. Pore volume compressibility $\alpha_p$ was assumed to be $3 \times 10^{-5}$ $psi^{-1}$ and compressibility of water $\beta$ was assumed to be $3.3 \times 10^{-6}$ $psi^{-1}$. These values are relatively constant for most problems commonly encountered in groundwater hydrology and are therefore assumed to be representative for the condition being studied.

A specific storage $S_s$ of $5.68 \times 10^{-5}$ $ft^{-1}$ was obtained by applying the formula

$$S_s = \rho \cdot g \cdot \phi \cdot (\alpha_p + \beta) \tag{A-4}$$

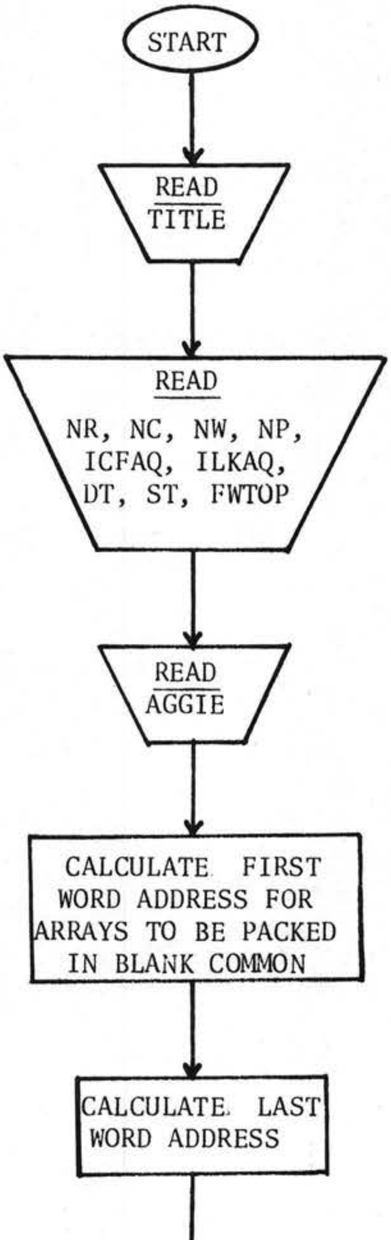
With a confined aquifer thickness set at 60 feet, a storage coefficient $S$ of 0.0034 was obtained.

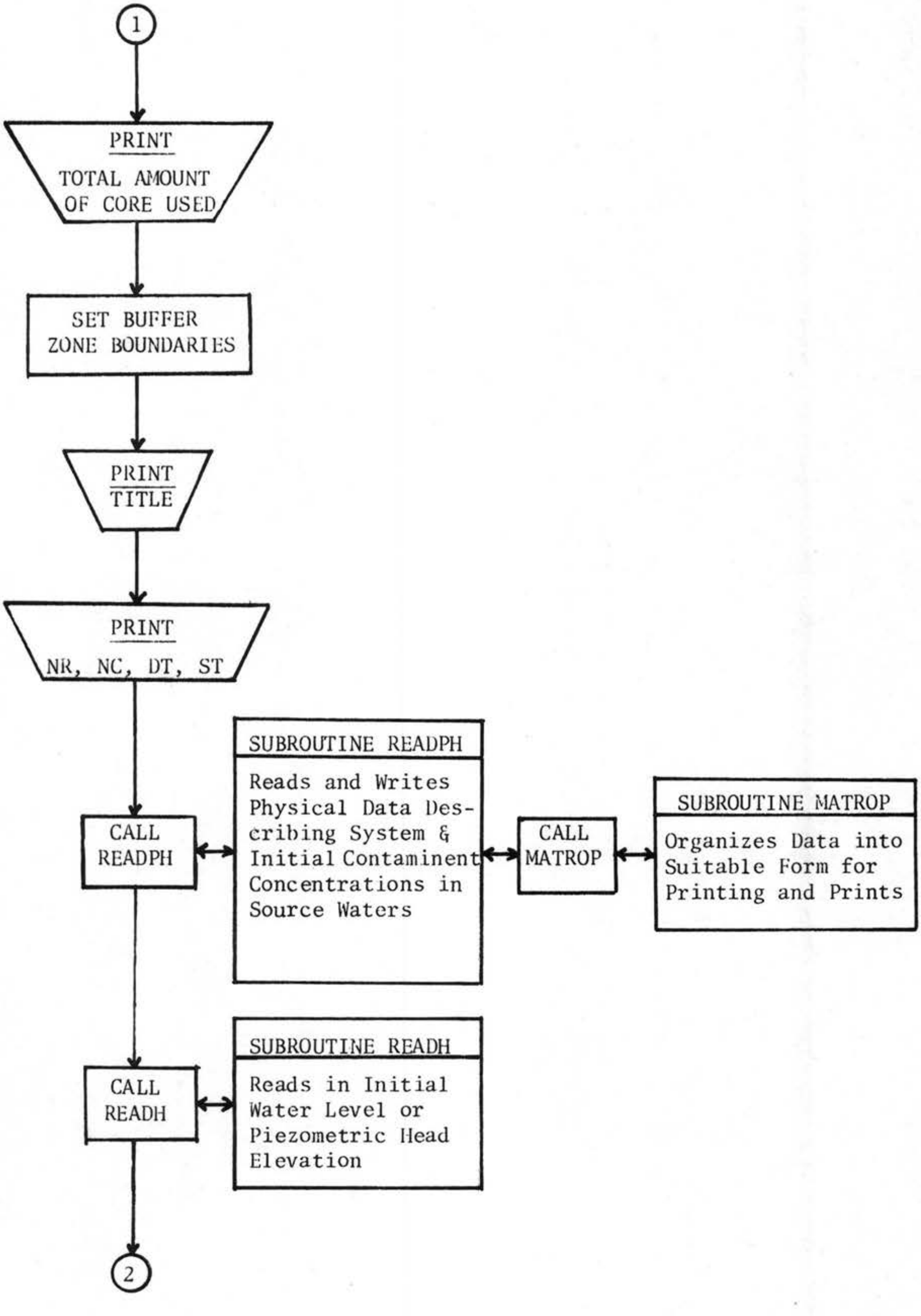
# APPENDIX B

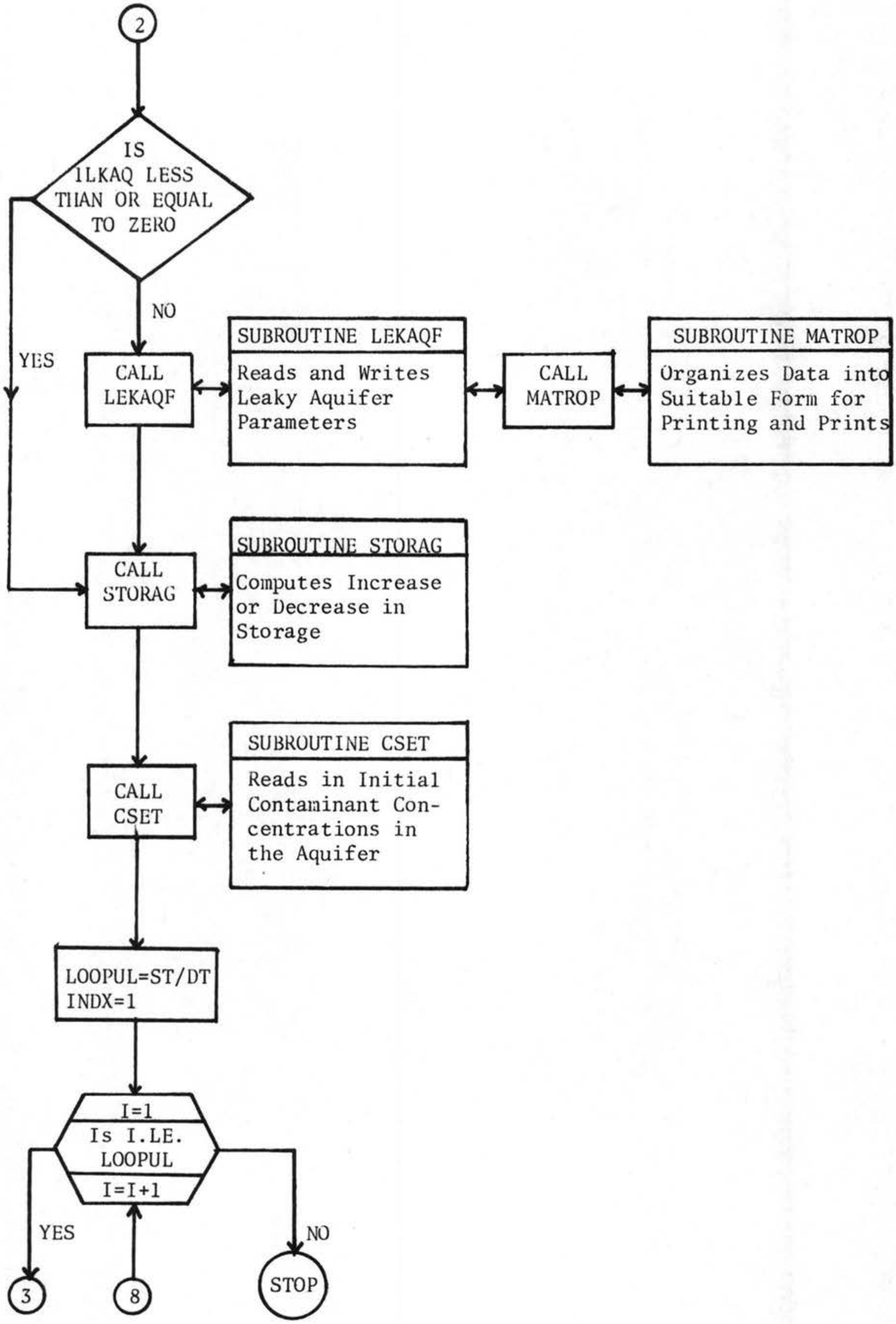
# PROGRAM FLOW CHART

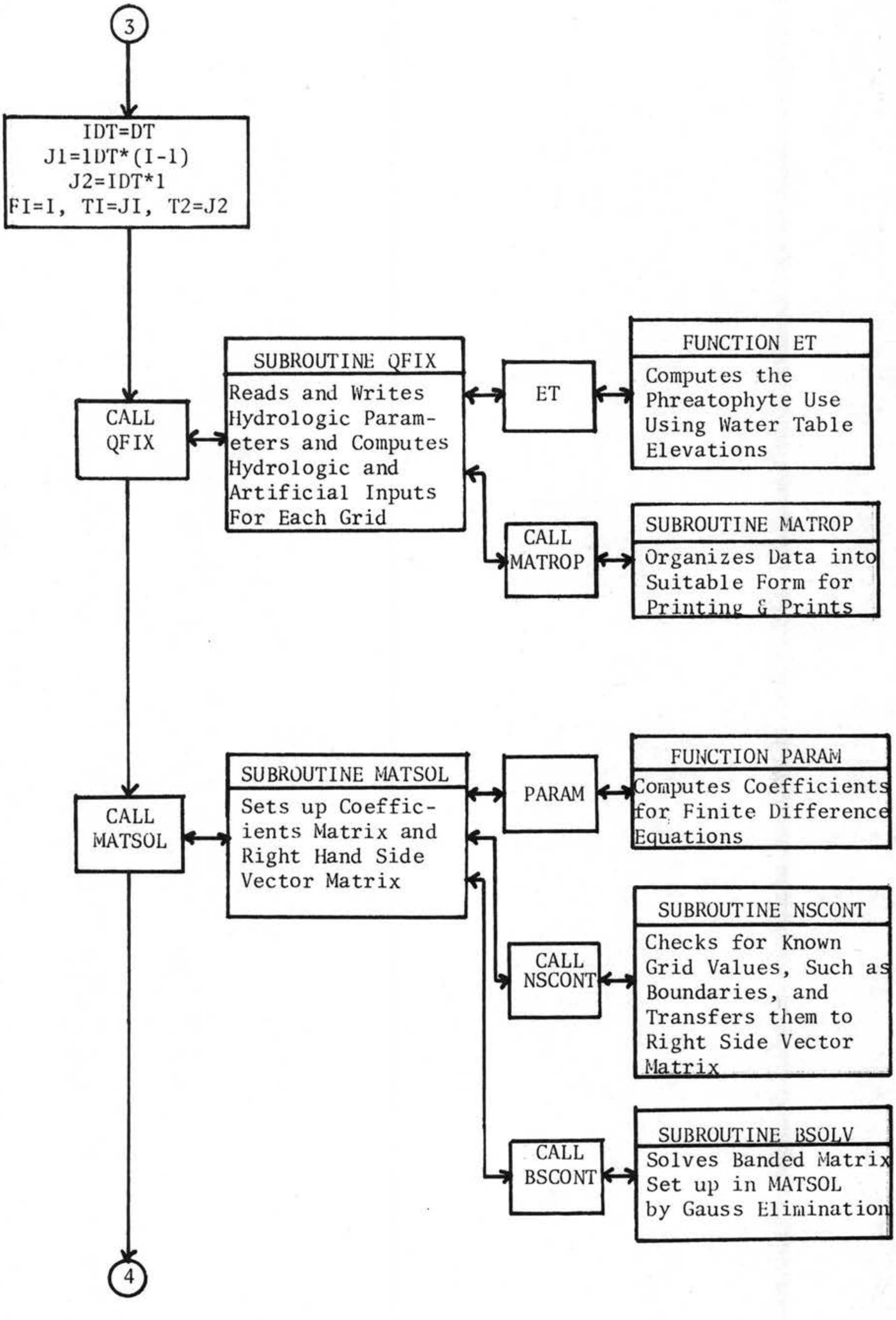
# APPENDIX B

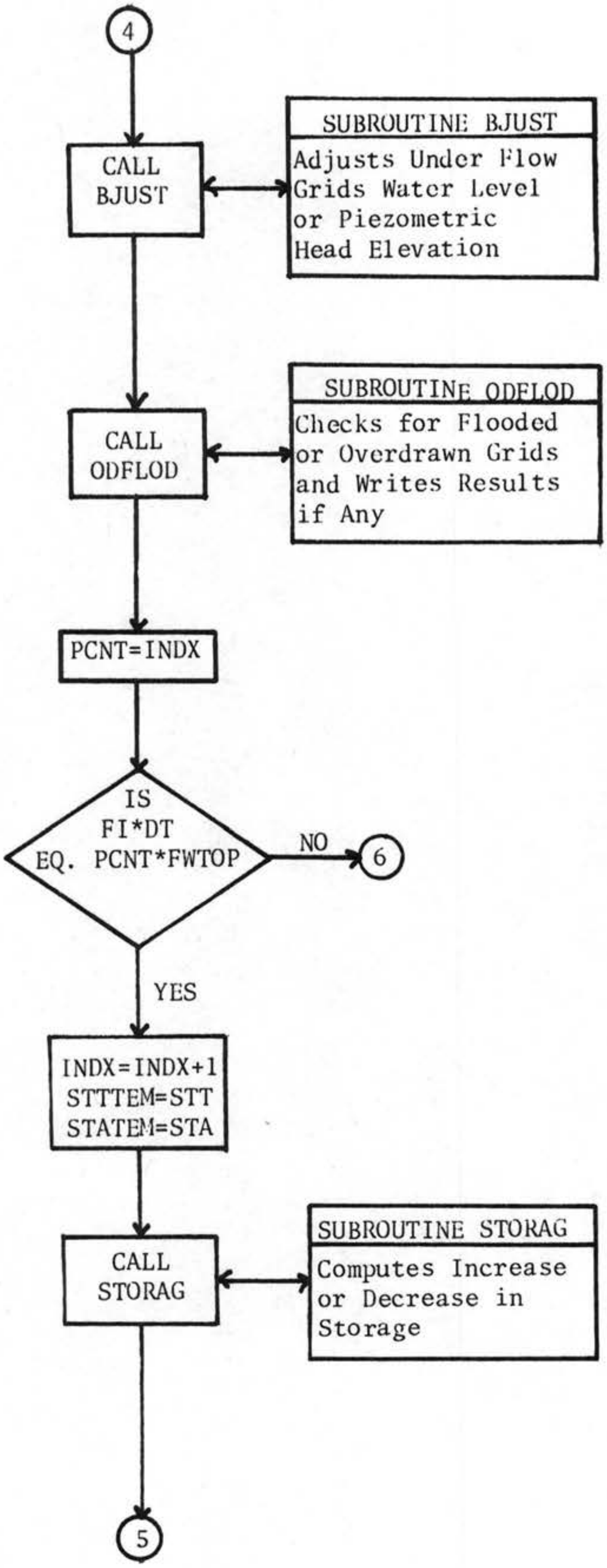
## PROGRAM FLOW CHART

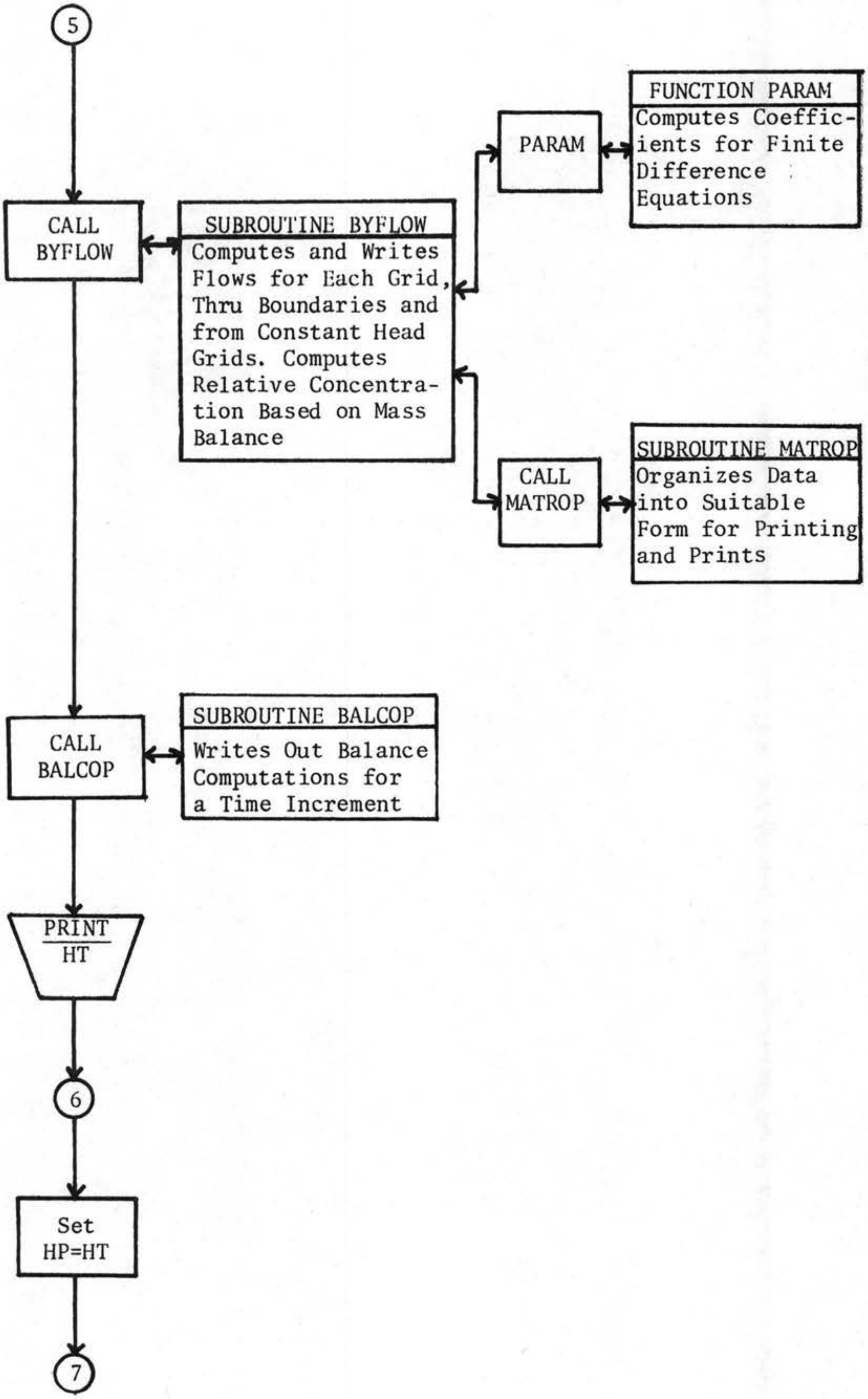


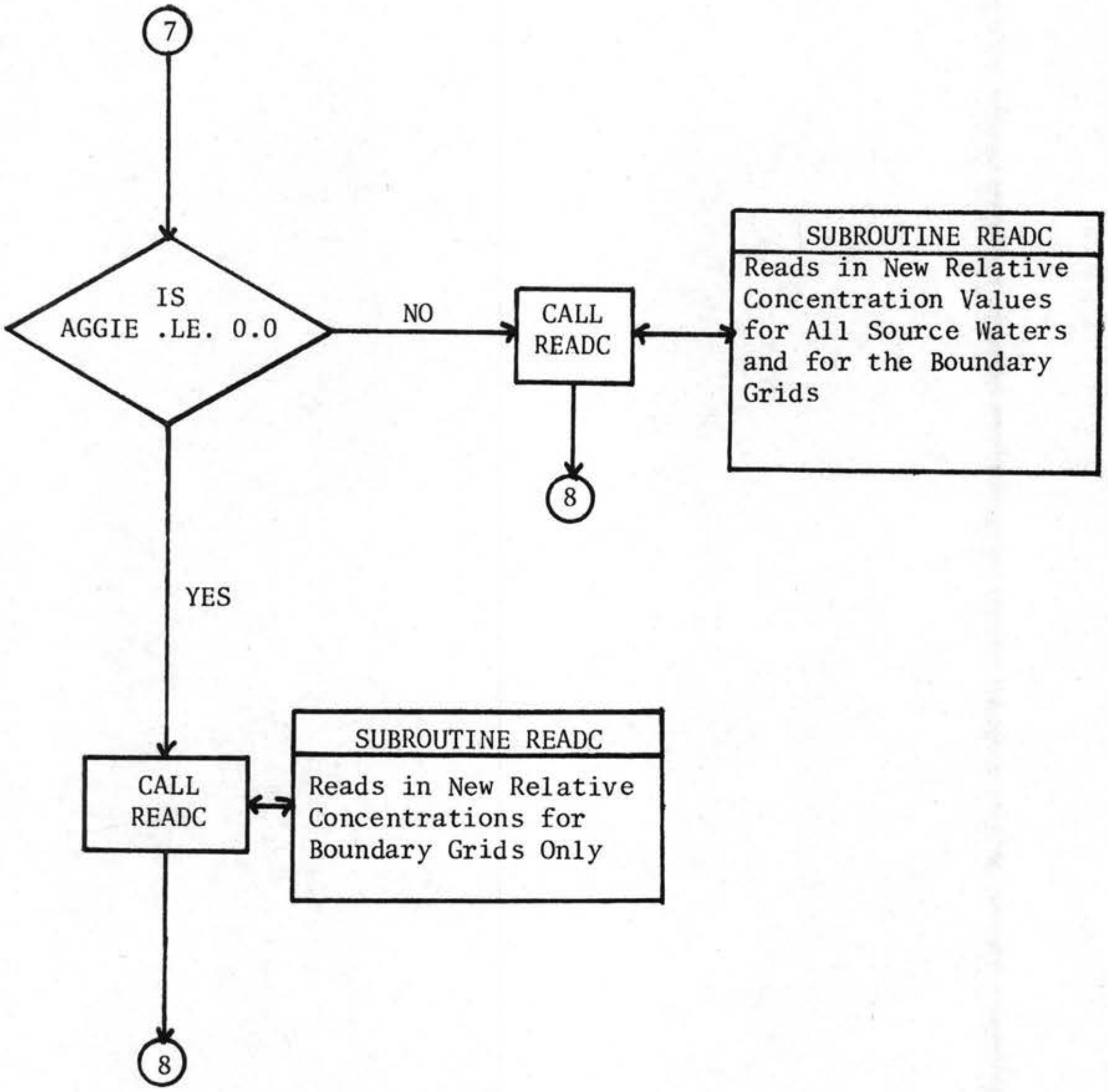

1
PRINT
TOTAL AMOUNT OF CORE USED
SET BUFFER ZONE BOUNDARIES
PRINT
TITLE
PRINT
NR, NC, DT, ST
CALL READPH
SUBROUTINE READPH
Reads and Writes Physical Data Describing System & Initial Contaminent Concentrations in Source Waters
CALL MATROP
SUBROUTINE MATROP
Organizes Data into Suitable Form for Printing and Prints
CALL READH
SUBROUTINE READH
Reads in Initial Water Level or Piezometric Head Elevation
2


2
IS
ILKAQ LESS
THAN OR EQUAL
TO ZERO
NO
YES
CALL
LEKAQF
SUBROUTINE LEKAQF
Reads and Writes
Leaky Aquifer
Parameters
CALL
MATROP
SUBROUTINE MATROP
Organizes Data into
Suitable Form for
Printing and Prints
CALL
STORAG
SUBROUTINE STORAG
Computes Increase
or Decrease in
Storage
CALL
CSET
SUBROUTINE CSET
Reads in Initial
Contaminant Con-
centrations in
the Aquifer
LOOPUL=ST/DT
INDX=1
I=1
Is I.LE.
LOOPUL
I=I+1
YES
NO
3
8
STOP


3
IDT=DT
J1=IDT*(I-1)
J2=IDT*1
FI=I, TI=JI, T2=J2
CALL QFIX
SUBROUTINE QFIX
Reads and Writes Hydrologic Parameters and Computes Hydrologic and Artificial Inputs For Each Grid
ET
FUNCTION ET
Computes the Phreatophyte Use Using Water Table Elevations
CALL MATROP
SUBROUTINE MATROP
Organizes Data into Suitable Form for Printing & Prints
CALL MATSOL
SUBROUTINE MATSOL
Sets up Coefficients Matrix and Right Hand Side Vector Matrix
PARAM
FUNCTION PARAM
Computes Coefficients for Finite Difference Equations
CALL NSCONT
SUBROUTINE NSCONT
Checks for Known Grid Values, Such as Boundaries, and Transfers them to Right Side Vector Matrix
CALL BSCONT
SUBROUTINE BSOLV
Solves Banded Matrix Set up in MATSOL by Gauss Elimination
4


4
CALL BJUST
SUBROUTINE BJUST
Adjusts Under Flow Grids Water Level or Piezometric Head Elevation
CALL ODFLOD
SUBROUTINE ODFLOD
Checks for Flooded or Overdrawn Grids and Writes Results if Any
PCNT=INDX
IS FI*DT EQ. PCNT*FWTOP
NO
6
YES
INDX=INDX+1
STTTEM=STT
STATEM=STA
CALL STORAG
SUBROUTINE STORAG
Computes Increase or Decrease in Storage
5


5
CALL BYFLOW
SUBROUTINE BYFLOW
Computes and Writes Flows for Each Grid, Thru Boundaries and from Constant Head Grids. Computes Relative Concentration Based on Mass Balance
PARAM
FUNCTION PARAM
Computes Coefficients for Finite Difference Equations
CALL MATROP
SUBROUTINE MATROP
Organizes Data into Suitable Form for Printing and Prints
CALL BALCOP
SUBROUTINE BALCOP
Writes Out Balance Computations for a Time Increment
PRINT
HT
6
Set HP=HT
7


7
IS
AGGIE .LE. 0.0
NO
CALL
READC
SUBROUTINE READC
Reads in New Relative Concentration Values for All Source Waters and for the Boundary Grids
8
YES
CALL
READC
SUBROUTINE READC
Reads in New Relative Concentrations for Boundary Grids Only
8

# APPENDIX C

# DESCRIPTION OF SUBPROGRAMS

# APPENDIX C

## DESCRIPTION OF SUBPROGRAMS

### Subroutine READPH

This subroutine reads and writes the physical data describing the study area. The following variables are read and printed: DX, DY, FK, Z, CS, CPPT, CAPW, CRCHR, CSQR, G, PHI, and PHIC. CA is also read but printed later. Coded values of CS are printed. Only one data card is required if all variables are uniform for each grid, otherwise each parameter that is variable must be read in matrix form. Variables DX and DY require only NC and NR values, respectively.

CALLED FROM: Main Program

SUBPROGRAMS USED: MATRØP

IMPORTANT VARIABLES: DX, DY, FK, Z, G, PHI, PHIC, CA, CS, CPPT, CAPW, CRCHR, CSQR

### Subroutine READH

This subroutine reads the initial coded water level or piezometric head elevations. H is decoded and set equal to HT and HP. One data card is required if the initial water level is horizontal, otherwise the entire H-matrix must be read.

CALLED FROM: Main Program

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: H, HT, HP

Subroutine LEKAQF

This subroutine reads and writes the leaky aquifer parameters. The following variables are read and printed: HL, TL, and FKL. One data card is required if these variables are uniform, otherwise each matrix that is variable must be read.

CALLED FROM: Main Program

SUBPROGRAMS USED: MATRØP

IMPORTANT VARIABLES: HL, TL, FKL

Subroutine CSET

This subroutine initializes the relative concentration throughout the aquifer.

CALLED FROM: Main Program

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: CØ, CT, H, G, CS

Subroutine STØRAG

This subroutine computes the initial storage and increase or decrease of storage. Total area and between station (between buffer zone boundaries) storage is calculated. Also storage of overlap areas is computed.

CALLED FROM: Main Program

SUBROUTINES USED: None

IMPORTANT VARIABLES: STA, STT, STØL, H, HT, Z

Subroutine QFIX

This subroutine reads and writes the hydrologic parameters. The hydrologic and artificial inputs are then calculated for each grid. A value of zero on the input card indicates a particular parameter is not used. The exception to this is the number of grids with phreatophyte use, NGPU. If NGPU is blank, the entire PHR matrix must be read, otherwise the number of grids specified is read. NGPU equal to zero indicates no phreatophyte use.

Coding PHR less than one indicates that phreatophyte use should be calculated every time increment from the previous time step water level elevation. The ET subprogram is used for this.

The factors considered in QFIX are (1) precipitation, (2) applied water as irrigation, (3) phreatophyte use, (4) wells, (5) recharge areas or lines, and (6) leaky aquifer conditions.

| | |
|---|---|
| CALLED FROM: | Main Program |
| SUBPROGRAMS USED: | ET |
| IMPORTANT VARIABLES: | PPT, CPT, YPT, APW, CAW, YAW, NGPU, PHR, YPR, WELL, RPUM, YPM, PIT, RCHR, YRC, Q, SQT, SQA, REPEAT, CPM |

Function ET

This subprogram computes the phreatophyte use for each grid using the water level elevations from the previous time step. If the depth of water table DTWT is negative, an error message is printed. It is anticipated this program, if used, will change with each study area.

CALLED FROM: QFIX

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: ET, DTWT

Subroutine MATSØL

This subroutine sets up the coefficient matrix, CMATRX, and the right hand side vector matrix, CR. CMATRX is a reduced matrix containing only the band of known values in the left side of the difference equations and is written vertically rather than diagonally. Its dimensions are (NR-2)*(NC-2) by 2*NR-3. The coefficients are computed using Function PARAM and checked for adjacent boundary values of H in subroutine NSCØNT. MATSØL treats known grid values of H. BSØLVE is used to solve the matrix equation set up.

CALLED FROM: Main Program

SUBPROGRAMS USED: PARAM, NSCØNT, BSØLVE

IMPORTANT VARIABLES: CMATRX, CR

Function PARAM

This subprogram computes the coefficients in the left side of the finite difference equation. For confined aquifer analysis, saturated thickness is compared to aquifer thickness and the smallest of the two is used to calculate the coefficient.

CALLED FROM: MATSØL, BYFLØW

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: PARAM

Subroutine NSCØNT

This subroutine transfers the coefficients, in CMATRX, multiplied by their respective H-value, to the right hand side vector matrix in case of adjacent head or known boundary conditions. It also sets coefficients equal to zero in case of adjacent impermeable grids.

CALLED FROM: MATSØL

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: None

Subroutine BSØLVE

This subroutine solves the matrix equation set up in MATSØL by Gauss Elimination. BSØLVE is designed specifically for a diagonal matrix that results from analysis of groundwater systems.

CALLED FROM: MATSØL

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: None

Subroutine BJUST

This subroutine adjusts the underflow boundary water level elevations. Gradients are calculated three grids in from the exterior boundary grids and the gradients are projected back to the exterior boundary grids to obtain new water level elevations. This calculation is performed at even time steps. At odd time steps the water level elevations are held constant and the exterior boundary grids are treated as constant head grids.

CALLED FROM: Main Program

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: H, HT

## Subroutine ØDFLØD

This subroutine checks for overdrawn or flooded grids. If either should occur, a message is printed indicating such. For confined aquifer analysis the flooded grid computations are bypassed. Total flooded and overdraw amounts are computed for the total area and between stations.

| | |
|---|---|
| CALLED FROM: | Main Program |
| SUBPROGRAMS USED: | None |
| IMPORTANT VARIABLES: | ØACFTT=ØVT, ØACFTA=ØVA, FACFTT=FVT, FACFTA=FVA |

## Subroutine BYFLØW

This subroutine computes flows for each grid. Total flow through model boundaries and buffer zone boundaries is calculated as well as flow into the system from constant head grids. The flow equation used is developed from the finite difference equations and uses particular values of the CMATRX. These values are transferred from MATSØL except for boundary values which are calculated in BYFLØW using Function PARAM. Flow is not allowed to or from an impermeable grid and between any two adjacent underflow grids. I-direction and J-direction flows are printed and flows from constant head grids are interpreted and printed as flow from river grids. Relative concentration calculations are made using the flow between grids.

| | |
|---|---|
| CALLED FROM: | Main Program |
| SUBPROGRAMS USED: | PARAM, MATRØP |
| IMPORTANT VARIABLES: | SQGGI, SQGGJ, SQBT, SQBA, SQR, SQRT, SQRA, CS, CPPT, CAPW, CRCHR, CSQR |

## Subroutine BALCØP

This subroutine writes the balance computations at the desired time steps specified by FWTØP. Mass balance for the entire area cannot always be obtained, due to accounting procedures used to compute mass flow at exterior boundary grids. However, for between stations, which refers to the area between the buffer zone boundaries, mass balance must always be satisfied except for the case when a confined grid becomes unconfined. This error should be small and is indicated by the "TOTALS" in the mass balance output being different than zero. To reduce this error, decrease the value of $\Delta t$. For confined aquifer analysis, a message is printed indicating if a grid becomes unconfined.

CALLED FROM: Main Program

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: SQA, SQT, SQRA, SQRT, SQBA, SQBT, STT, STTTEM, STA, STATEM, STØL, ØVA, ØVT

## Subroutine MATRØP

This subroutine organizes data or results into a suitable form for printing and then prints.

CALLED FROM: READPH, LEKAQF, QFIX, BYFLØW

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: NR=NØRØW, NC=NØCØL

Subroutine READC

This subroutine reads in new relative concentration values for all source waters and the boundary grids for each time increment of analysis. Execution of this subroutine is controlled by the value AGGIE. If AGGIE is less than or equal to zero, only new concentrations for the boundary grids will be read in. If AGGIE is greater than zero, new values for each source water throughout the grid network can be read in as a single value. Variable concentrations must be read in matrix form. Boundary grid concentrations are read in one value per card for each grid other than impermeable boundaries.

CALLED FROM: Main Program

SUBPROGRAMS USED: None

IMPORTANT VARIABLES: CPPT, CAPW, CRCHR, CSQR, CØ, AGGIE

# APPENDIX D

# PROGRAM LISTING

# PROGRAM WTQUAL2

```
      PROGRAM WTQUAL2
C
C
C     PROGRAM TO COMPUTF ARTIFICIAL AND HYDROLCCIC INFLUENCF CN GRCUND
C       WATER LEVEL.
C
C     BASIC PROGRAM DEVELOPED BY THE GROUNDWATER STAFF AT C.S.U.
C
C     MODIFIED FOR UNCONFINED AND CCNFINED LEAKY AQUIFERS, CYNAMIC COFE
C     ALLOCATION  AND STRIP MINE WATER QUALITY BY D.K. SUNACA 1976.
C     MODIFIED AS A GROUNDWATER QUALITY MANAGEMENT MOCEL BY L.W. PITTMAN
C     1977.
C
C     SEE USERS MANUAL FOR DATA INPUT.
C
C     PROGRAM USES BUFFER ZONES. IT SHOULD BE NOTED THAT MASS BALANCE
C       OCCURS FOR THE CASE OF CONSTANT HEAD OR IMPERMEABLE BOUNDARIES.
C       FOR THE CASE OF UNDERFLCW BOUNDARIES, CNLY MASS BALANCE
C       BETWEEN BUFFER ZONES SHOULD BE EXPECTEC.  BUFFER ZONES ARE
C       SET IN PROGRAM AND FOR EFFECTIVE USE, NR.GT.7  ANC  NC.GT.7 .
C       LCIW=LEFT (J) BUFFER ZONE
C       LCIE=RIGHT (J) BUFFER ZONE
C       LCJW=TOP (I) BUFFER ZONE
C       LCJE=BOTTOM (I) BUFFER ZONE
C
C     FOR EXPLINATION OF VARIABLES AND SUBRCUTINES, SEE SUBROUTINES.
C
C     CONTROL VARIABLES
C       NR=NUMBER OF ROWS
C       NC=NUMBER OF COLUMNS
C       NR SHOULD ALWAYS BE LESS THAN OR EQUAL TO NC
C       NW=MAXIMUM NUMBER OF WELLS
C       NP=MAXIMUM NUMBER OF RECHARGE PITS
C       ICFAQ=1 FOR CONFINED AQUIFER ANALYSIS, CTHERWISE BLANK
C       ILKAQ=1 FOR LEAKY AQUIFER CONDITIONS, CTHERWISE BLANK
C       DT=TIME INCREMENT (DAYS)
C       ST=TOTAL TIME OF ANALYSIS (CAYS)
C       FWTOP=DESIRED TIME OF OUTPUT (MULTIFLE OF CT)
C
C       NA=NUMBER OF ROWS IN REDUCEC BAND MATRIX
C       NB=NUMBER CF COLUMNS IN REDUCED BAND MATRIX
C       INYP=NUMBER OF TIME INCREMENTS FER YEAR
C       IFK, IPHI ETC.=FIRST WORD ADDRESS OF FK, PHI ETC. ARRAYS
C
C
      DIMENSION TITLE(8)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FWTOP
      COMMON /BLK2/ STA,STOL,STT,SQA,SQT,SQFA,SQBA,SQRT,SQBT,CVA,OVT
      COMMON C(2)
C
      READ (5,200) TITLE
      READ (5,220) NR,NC,NW,NP,ICFAQ,ILKAQ,DT,ST,FWTOP
      READ (5,270) AGGIE
C
C
C     IF AGGIE EQUALS 1, NEW CONCENTRATIONS MUST BE READ IN FCR EACH SOURCE
C     WATER AT THE BEGINNING OF EACH TIME INCREMENT.
C     IF AGGIE EQUAL 0, NEW CONCENTRATICNS MUST BE READ IN CNLY FOR CONSTANT
C     HEAD AND CONSTANT GRADIENT BOUNDAFY GRIDS AT THE BEGINNING OF EACH TIME
C     INCREMENT.
C     IF AGGIE IS LESS THAN 0, OLD CONCENTRATICN VALUES WILL BE USED FOR ALL
C     SOURCE WATERS AND BOUNDARY GRIDS.
```

```
C
C
      NA=(NP-2)*(NC-2)
      NB=2*NR-3
C
      INYR=360.0/DT
C
      IDC=NR*NC
      IFK=1
      IPHI=IDC+1
      IZ=2*IDC+1
      IG=3*IDC+1
      IDX=4*IDC+1
      IDY=5*IDC+1
      ICA=6*IDC+1
      IH=7*IDC+1
      IHT=8*IDC+1
      IHP=9*IDC+1
      IQ=10*IDC+1
      IWELL=11*IDC+1
      IPIT=12*IDC+1
      IPHR=13*IDC+1
      ISQGGI=14*IDC+1
      ISQGGJ=15*IDC+1
      ISQR=16*IDC+1
      IA=17*IDC+1
      IB=18*IDC+1
      IPHRTMP=19*IDC+1
      IHF=20*IDC+1
      ICO=21*IDC+1
      ICT=22*IDC+1
      ICS=23*IDC+1
      IAREA=24*IDC+1
      IOPPT=25*IDC+1
      IOAPW=26*IDC+1
      IORCHR=27*IDC+1
      IOPHR=28*IDC+1
      IOPUM=29*IDC+1
      IQLEAK=30*IDC+1
      ICPPT=31*IDC+1
      ICAPW=32*IDC+1
      ICRCHR=33*IDC+1
      ICPHR=34*IDC+1
      ICPUM=35*IDC+1
      ICLEAK=36*IDC+1
      ICSQR=37*IDC+1
      IPHIC=ICS+ICFAQ*IDC
      IHL=IPHIC+ILKAQ*IDC
      ITL=IHL+ILKAQ*IDC
      IFKL=ITL+ILKAQ*IDC
      IEND1=38*IDC+ICFAQ*IDC+ILKAQ*3*IDC
C
      IYPT=IEND1+1
      IYPR=IYPT+INYR
      IYAW=IYPR+INYR
      IYPM=IYAW+INYR
      ICPM=IYPM+NW*INYR
      IRPUM=ICPM+NW
      IYRC=IRPUM+NW
      IRCHR=IYRC+NP*INYR
      IEND2=IEND1+3*INYR+NW*INYR+2*NW+NP*INYR+NP+1
C
      ICMATRX=IEND2+1
      ICR=IEND2+(NA*NB)+1
      IEND3=IEND2+NA+(NA*NB)
C
      LWA=LOCF(C(IEND3))
      WRITE (6,230) LWA
      CALL CORF (LWA)
      DO 100 LI=1,IEND3
         C(LI)=UNDEF
  100 CONTINUE
C
      LCIW=3
      LCIE=NC-2
      LCJW=3
      LCJE=NR-2
C
      WRITE (6,210) TITLE
      IF (ILKAQ.LE.0) GO TO 110
      WRITE (6,250)
```

```
      GO TO 130
  110 IF (ICFAQ.LE.0) GO TO 120
      WRITE (6,240)
      GO TO 130
  120 WRITE (6,260)
  130 WRITE (6,190) NR,NC,DT,ST
C
      CALL READFH (NR,NC,C(IFK),C(IFHI),C(IZ),C(IG),C(IDX),C(IDY),C(ICA)
     1,C(IPHIC),C(ICPPT),C(ICAPW),C(ICRCHR),C(ICSGR),C(ICS),C(IAREA),TAR
     2EA)
C
      CALL READH (NR,NC,C(IH),C(IHP),C(IHT),C(IHF),LBC,RBC,TBC,BBC)
C
      IF (ILKAQ.LE.0) GO TO 140
      CALL LEKAQF (NR,NC,C(IHL),C(ITL),C(IFKL))
C
  140 CALL STORAG (NR,NC,C(IH),C(IHT),C(IZ),C(IDX),C(IDY),C(IPHI),C(IG),
     1C(IPHIC))
      CALL CSET (NR,NC,C(ICO), C(ICT), C(IH), C(IG),C(ICS))
C
      LOOPUL=ST/DT
      INDX=1
C
      DO 170 I=1,LOOPUL
C
         IDT=DT
         J1=IDT*(I-1)
         J2=IDT*I
         FI=I
         T1=J1
         T2=J2
C
         CALL QFIX (NR,NC,C(IDX),C(IDY),C(ICA),C(IH),C(IZ),C(IHT),I,C(IC
     1   ),NW,NP,C(IPHR),C(IWELL),C(IPIT),C(IYPT),C(IYAW),C(IYPR),C(IYPM
     2   ),C(IRPUM),C(ICPM),C(IYRC),C(IRCHR),INYR,C(IHL),C(ITL),C(IFKL),
     3   C(IG),C(IPHRTMP),C(IQPPT),C(IQAPW),C(IQRCHR),C(IQPHR),C(IQPUM),
     4   C(IQLEAK),C(IAREA),TAREA)
C
         CALL MATSOL (NR,NC,NA,NB,C(IFK),C(IPHI),C(IH),C(IHT),C(IZ),C(ID
     1   X),C(IDY),C(IQ),C(ICMATRX),C(ICR),C(IA),C(IB),C(IG),C(IPHIC),C(
     2   IHP),C(IHF))
C
         CALL BJUST (NR,NC,C(IH),C(IHT),C(IHP),C(IDX),C(IDY),I)
C
         CALL ODFLOD (NR,NC,C(IH),C(IHT),C(IZ),C(IG),C(IPHI),C(IDX),C(ID
     1   Y),C(IPHIC))
C
         STTTEM=STT
         STATEM=STA
         CALL STORAG (NR,NC,C(IH),C(IHT),C(IZ),C(IDX),C(IDY),C(IPHI),C(I
     1   G),C(IPHIC))
C
         PCNT=INDX
         IF ((FI*DT).NE.(PCNT*FWTOP)) GO TO 150
         INDX=INDX+1
C
         CALL BYFLOW (NR,NC,NA,NB,C(IFK),C(IH),C(IHF),C(IZ),C(IDX),C(IDY
     1   ),C(ISQGGI),C(ISQGGJ),C(ISQR),C(ICMATRX),C(IA),C(IB),C(IHF),C(I
     2   G),I,C(ICO),C(ICT),C(IPHI),C(IPHIC),C(ICS),C(IQPPT),C(IQAPW),C(
     3   IQRCHR),C(IQPHR),C(IQPUM),C(IQLEAK),C(ICPPT),C(ICAPW),C(ICRCHR)
     4   ,C(ICSQR),C(IQ),C(ICPUM),C(ICLEAK),C(ICPHR))
C
         CALL BALCOP (J1,J2,I,STTTEM,STATEM)
C
         WRITE (6,180) T2
         CALL MATROP (NR,NC,C(IHT))
C
  150    NCT=0
         DO 160 L=1,NC
         DO 160 K=1,NR
            C(IHP+NCT)=C(IHT+NCT)
            NCT=NCT+1
  160    CONTINUE
      IF (I .EQ. LOOPUL) GO YO 170
      CALL READC (NR,NC,C(ICAPW),C(ICRCHR),C(ICSGR),C(ICC),LBC,RBC,TBC,
     1BBC,AGGIE)
  170 CONTINUE
      STOP
C
  180 FORMAT (1H1,44X, 22HHEAD MAP AT TIME LEVEL,F10.2,/1H ,52X, 18H(FEE
     1T ABOVE DATUM))
```

```
  190 FORMAT (15H-ROW DIMENSION=I4,21H     COLUMN DIMENSION=I4,24H    TIM
     1E INCREMENTED BY G9.2,5H DAYS,27H     TOTAL TIME OF ANALYSIS G9.2,5
     2H DAYS)
  200 FORMAT (8A10)
  210 FORMAT (1H1,/////,27X,8A10)
  220 FORMAT (6I5,5F10.1)
  230 FORMAT (1H ,///, 20H   FIELD LENGTH =    ,020)
  240 FORMAT (1H-,47X, 25HCONFINED AQUIFER ANALYSIS)
  250 FORMAT (1H-,48X, 22HLEAKY AQUIFER ANALYSIS)
  260 FORMAT (1H-,46X, 27HUNCONFINED AQUIFER ANALYSIS)
  270 FORMAT (1F10.1)
C
      END
```

# SUBROUTINE READPH

```
      SUBROUTINE READPH (NR,NC,FK,PHI,Z,G,DX,DY,CA,PHIC,CPPT,CAPW,CRCHR,
     2CSQR,CS,AREA,TAREA)
C
C
C     THIS SUBROUTINE READS AND WRITES THE PHYSICAL DATA DESCRIBING
C       THE SYSTEM.
C       FK=PERMEABILITY (FEET/DAY)
C       PHI=EFFECTIVE POROSITY
C       Z=BEDROCK ELEVATION (FEET)
C       G=GROUND SURFACE ELEVATION, OR TOP OF CONFINED AQUIFER (FEET)
C       DX=X-DIMENSION OF GRID (FEET)
C       DY=Y-DIMENSION OF GRID (FEET)
C       CA=FRACTION OF GRID THAT WATER IS APPLIED (DECIMAL)
C       PHIC=CONFINED AQUIFER STORAGE COEFFICIENT
C       DLX=UNIFORM DX
C       DLY=UNIFORM DY
C       FFK=UNIFORM FK
C       ZZ=UNIFORM Z
C       GG=UNIFORM G
C       PPHI=UNIFORM PHI
C       CCA=UNIFORM CA
C       PPHIC=UNIFORM PHIC
C        CS=RELATIVE CONCENTRATION OF CONTAMINANT IN AQUIFER (DECIMAL)
C        CPPT=RELATIVE CONCENTRATION OF CONTAMINANT IN PRECIPITATION
C        CAPW=RELATIVE CONCENTRATION OF CONTAMINANT IN WATER APPLIED AS
C             IRRIGATION
C        CRCHR=RELATIVE CONCENTRATION OF CONTAMINANT IN RECHARGE WATERS
C        CSQR=RELATIVE CONCENTRATION OF CONTAMINANT FROM CONSTANT HEAD
C             SOURCES
C        AREA=AREA OF EACH GRID
C        TAREA=TOTAL AREA COVERED BY THE GRID NETWORK
C
      DIMENSION FK(NR,NC), PHI(NR,NC), Z(NR,NC), G(NR,NC), DX(NR,NC), DY
     1(NR,NC), CA(NR,NC), PHIC(NR,NC), CS(NR,NC), AREA(NR,NC), CPPT(NR,
     2NC), CAPW(NR,NC), CRCHR(NR,NC), CSQR(NR,NC)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FKTOP
C
      DO 110 J=1,NR
      DO 110 K=1,NC
         FK(J,K)=0.0
         Z(J,K)=0.0
         G(J,K)=0.0
         PHI(J,K)=0.0
         CA(J,K)=0.0
         PHIC(J,K)=0.0
         CS(J,K)=0.0
         CPPT(J,K)=0.0
         CAPW(J,K)=0.0
         CRCHR(J,K)=0.0
         CSQR(J,K)=0.0
  110 CONTINUE
C
      READ (5,440) DLX,DLY,FFK,ZZ,GG,PPHI,CCA,PPHIC
C
      IF (DLX.LE.0.0) GO TO 130
```

```
      DO 120 J=1,NC
      DO 120 I=1,NR
  120 DX(I,J)=DLX
      GO TO 150
  130 READ (5,440) (DX(1,J),J=1,NC)
      DO 140 I=2,NR
      DO 140 J=1,NC
  140 DX(I,J)=DX(1,J)
  150 CONTINUE
C
      IF (DLY.LE.0.0) GO TO 170
      DO 160 J=1,NC
      DO 160 I=1,NR
  160 DY(I,J)=DLY
      GO TO 190
  170 READ (5,440) (DY(I,1),I=1,NR)
      DO 180 J=2,NC
      DO 180 I=1,NR
  180 DY(I,J)=DY(I,1)
  190 CONTINUE
      TAREA=0.0
      DO 195 J=1,NC
      DO 195 I=1,NR
      AREA(I,J)=DX(I,J)*DY(I,J)
      TAREA=TAREA+AREA(I,J)
  195 CONTINUE
C
      IF (FFK.LE.0.0) GO TO 210
      DO 200 J=1,NR
      DO 200 K=1,NC
  200 FK(J,K)=FFK
      GO TO 220
  210 READ (5,440) FK
C
  220 IF (ZZ.NE.0.0) GO TO 230
      IF (SIGN(1.0,ZZ).LT.0.0) GO TO 250
  230 DO 240 J=1,NR
      DO 240 K=1,NC
  240 Z(J,K)=ZZ
      GO TO 260
  250 READ (5,440) Z
C
  260 IF (GG.NE.0.0) GO TO 270
      IF (SIGN(1.0,GG).LT.0.0) GO TO 290
  270 DO 280 J=1,NR
      DO 280 K=1,NC
  280 G(J,K)=GG
      GO TO 300
  290 READ (5,440) G
C
  300 IF (PPHI.LE.0.0) GO TO 320
      DO 310 J=1,NR
      DO 310 K=1,NC
  310 PHI(J,K)=PPHI
      GO TO 330
  320 READ (5,440) PHI
C
  330 IF (CCA.NE.0.0) GO TO 340
      IF (SIGN(1.0,CCA).LT.0.0) GO TO 360
  340 DO 350 J=1,NC
      DO 350 I=1,NR
  350 CA(I,J)=CCA
      GO TO 370
  360 READ (5,440) CA
C
  370 IF (ICFAO.LE.0) GO TO 400
      IF (PPHIC.LE.0.0) GO TO 390
      DO 380 I=1,NR
      DO 380 J=1,NC
  380 PHIC(I,J)=PPHIC
      GO TO 400
  390 READ (5,440) PHIC
  400 READ (5,445) CSS
      IF(CSS.LE.0.0) GO TO 610
      DO 600 J=1,NC
      DO 600 I=1,NR
  600 CS(I,J)=CSS
      GO TO 615
  610 READ (5,440) CS
  615 READ (5,445) CCPPT
      IF (CCPPT.LT.0.0) GO TO 630
```

```
      DO 620 J=1,NC
      DO 620 I=1,NR
  620 CPPT(I,J)=CCPPT
      GO TO 640
  630 READ (5,440) CPPT
C
  640 READ (5,445) CCAPW
      IF (CCAPW.LT.0.0) GO TO 650
      DO 660 J=1,NC
      DO 660 I=1,NR
  660 CAPW(I,J)=CCAPW
      GO TO 670
  650 READ (5,440) CAPW
C
  670 READ (5,445) CCRCHR
      IF (CCRCHR.LT.0.0) GO TO 680
      DO 690 J=1,NC
      DO 690 I=1,NR
  690 CRCHR(I,J)=CCRCHR
      GO TO 700
  680 READ (5,440) CRCHR
C
  700 READ (5,445) CCSOR
      IF (CCSOR.LT.0.0) GO TO 710
      DO 720 J=1,NC
      DO 720 I=1,NR
  720 CSOR(I,J)=CCSOR
      GO TO 730
  710 READ (5,440) CSOR
  730 CONTINUE
C
      WRITE (6,530)
      CALL MATROP (NR,NC,CS)
      WRITE (6,540)
      CALL MATROP (NR,NC,CPPT)
      WRITE (6,550)
      CALL MATROP (NR,NC,CAPW)
      WRITE (6,560)
      CALL MATROP (NR,NC,CRCHR)
      WRITE (6,570)
      CALL MATROP (NR,NC,CSOR)
      WRITE (6,450)
      CALL MATROP (NR,NC,DX)
      WRITE (6,460)
      CALL MATROP (NR,NC,DY)
      IF (ICFAQ.GT.0) GO TO 410
      WRITE (6,470)
      GO TO 420
  410 WRITE (6,510)
  420 CALL MATROP (NR,NC,G)
      WRITE (6,480)
      CALL MATROP (NR,NC,Z)
      WRITE (6,490)
      CALL MATROP (NR,NC,PHI)
      IF (ICFAQ.LE.0) GO TO 430
      WRITE (6,520)
      CALL MATROP (NR,NC,PHIC)
  430 WRITE (6,500)
      CALL MATROP (NR,NC,FK)
      RETURN
C
  440 FORMAT (8F10.1)
  445 FORMAT (1F10.1)
  450 FORMAT (1H1,40X, 50HDELTA-X MAP,SPACING ACROSS IN J-DIRECTION   (FE
     1ET)  ,/)
  460 FORMAT (1H1,41X, 47HDELT-Y MAP, SPACING DOWN IN I-DIRECTION   (FEET
     1),/)
  470 FORMAT (1H1,44X, 41HSURFACE ELEVATION MAP   (FEET ABOVE DATUM),/)
  480 FORMAT (1H1,44X, 41HBEDROCK ELEVATION MAP   (FEET ABOVE DATUM),/)
  490 FORMAT (1H1,55X, 18HSPECIFIC YIELD MAP,/)
  500 FORMAT (1H1,46X, 28HPERMEABILITY MAP   (FEET/DAY),/)
  510 FORMAT (1H1,30X, 57HTOP OF CONFINED AQUIFER ELEVATION MAP   (FEET A
     1BOVE DATUM),/)
  520 FORMAT (1H1,39X, 40HCONFINED AQUIFER STORAGE COEFFICIENT MAP,/)
  530 FORMAT (1H1,51X, 33HINITIAL AQUIFER CONCENTRATION MAP,/)
  540 FORMAT (1H1,49X, 39HINITIAL PRECIPITATION CONCENTRATION MAP,/)
  550 FORMAT (1H1,49X, 39HINITIAL APPLIED WATER CONCENTRATION MAP,/)
  560 FORMAT (1H1,52X, 34HINITIAL RECHARGE CONCENTRATION MAP,/)
  570 FORMAT (1H1,48X, 38HCONSTANT HEAD GRID CONCENTRATION MAP,/)
C
      END
```

# SUBROUTINE READH

```
      SUBROUTINE READH (NR,NC,H,HP,HT,HF,LBC,RBC,TBC,BBC)
C
C
C     THIS SUBROUTINE READS IN AN INITIAL WATER TABLE ELEVATION OR
C       HEAD FOR COMPARING WATER LEVEL CHANGES.
C       H=INITAL WATER TABLE ELEVATION OR HEAD (FEET)
C       HT=PRESENT WATER TABLE ELEVATION OR HEAD (FEET)
C       HP=WATER TABLE ELEVATION OR HEAD AT PREVIOUS TIME LEVEL (FEET)
C       HW=HORIZONTAL WATER LEVEL
C       LBC=LEFT BOUNDARY CODE
C       RBC=RIGHT BOUNDARY CODE
C       TBC=TOP BOUNDARY CODE
C       BBC=BOTTOM BOUNDARY CODE
C     IDENTIFICATION OF BOUNDARY VALUES OF H.
C       H(I,J) LESS THAN 10,000 - WATER TABLE ELEVATION (NO BOUNDARY)
C       H(I,J) GREATER THAN 10000 BUT LESS THAN 20000 - IMPERMEABLE
C       H(I,J) GREATER THAN 20000 BUT LESS THAN 30000 - UNDERFLOW
C       H(I,J) GREATER THAN 30000 BUT LESS THAN 40000 - CONSTANT HEAD
C
      DIMENSION H(NR,NC), HT(NR,NC), HP(NR,NC), HF(NR,NC)
      REAL LBC
C
      READ (5,220) HW,LBC,RBC,TBC,BBC
C
      IF (HW.LE.0.0) GO TO 140
      DO 110 I=1,NR
      DO 110 J=1,NC
  110 H(I,J)=HW
      DO 120 I=1,NR
         H(I,1)=LBC+HW
         H(I,NC)=RBC+HW
  120 CONTINUE
      DO 130 J=1,NC
         H(1,J)=TBC+HW
         H(NR,J)=BBC+HW
  130 CONTINUE
      GO TO 150
C
  140 READ (5,220) H
  150 DO 210 J=1,NC
      DO 210 I=1,NR
         KK=H(I,J)/10000.+1
         GO TO (160,170,180,190), KK
  160    HT(I,J)=H(I,J)
         GO TO 200
  170    HT(I,J)=H(I,J)-10000.
         GO TO 200
  180    HT(I,J)=H(I,J)-20000.
         GO TO 200
  190    HT(I,J)=H(I,J)-30000.
  200    HP(I,J)=HT(I,J)
         HF(I,J)=HT(I,J)
  210 CONTINUE
      RETURN
C
  220 FORMAT (8F10.1)
C
      END
```

# SUBROUTINE LEKAQF

```
      SUBROUTINE LEKAQF (NR,NC,HL,TL,FKL)
C
C
C     THIS SUBROUTINE READS IN LEAKY AQUIFER PARAMETERS.
C       HL=CONSTANT HEAD VALUE CAUSING LEAK (FEET)
C       TL=THICKNESS OF LEAKY LAYER (FEET)
C       FKL=PERMEABILITY OF LEAKY LAYER (FEET/DAY)
C
      DIMENSION HL(NR,NC), TL(NR,NC), FKL(NR,NC)
C
```

```
      DO 110 I=1,NR
      DO 110 J=1,NC
         HL(I,J)=0.0
         TL(I,J)=0.0
         FKL(I,J)=0.0
  110 CONTINUE
      READ (5,210) HHL,TTL,FFKL
      IF (HHL.LE.0.0) GO TO 130
      DO 120 I=1,NR
      DO 120 J=1,NC
  120 HL(I,J)=HHL
      GO TO 140
  130 READ (5,210) HL
  140 IF (TTL.LE.0.0) GO TO 160
      DO 150 I=1,NR
      DO 150 J=1,NC
  150 TL(I,J)=TTL
      GO TO 170
  160 READ (5,210) TL
  170 IF (FFKL.LE.0.0) GO TO 190
      DO 180 I=1,NR
      DO 180 J=1,NC
  180 FKL(I,J)=FFKL
      GO TO 200
  190 READ (5,210) FKL
  200 CONTINUE
      WRITE (6,220)
      CALL MATROP (NR,NC,HL)
      WRITE (6,230)
      CALL MATROP (NR,NC,TL)
      WRITE (6,240)
      CALL MATROP (NR,NC,FKL)
      RETURN
C
  210 FORMAT (8F10.1)
  220 FORMAT (1H1,/////,38X, 44HHEAD MATRIX CAUSING LEAK  (FEET ABOVE DA
     1TUM),//)
  230 FORMAT (1H1,/////,44X, 32HTHICKNESS OF LEAKY LAYER  (FEET),//)
  240 FORMAT (1H1,/////,36X, 48HVERTICAL PERMEABILITY OF LEAKY LAYER  (F
     1EET/DAY),//)
C
      END
```

# SUBROUTINE STORAG

```
      SUBROUTINE STORAG (NR,NC,H,HT,Z,DX,DY,S,G,SC)
C
C
C     THIS SUBROUTINE COMPUTES THE INCREASE OR DECREASE IN STORAGE.
C       STA=BETWEEN STATIONS STORAGE (AF)
C       STT=TOTAL AREA STORAGE (AF)
C       STOL=OVERLAP AREA STORAGE (AF)
C
      DIMENSION H(NR,NC), HT(NR,NC), Z(NR,NC), DX(NR,NC), DY(NR,NC), S(N
     1R,NC), G(NR,NC), SC(NR,NC)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FKTOP
      COMMON /BLK2/ STA,STOL,STT,SQA,SQT,SQBA,SQBA,SQBT,SQBT,OVA,OVT
C
      NC1=NC-1
      NR1=NR-1
      STT=0.0
      STA=0.0
      DO 130 L=2,NC1
      DO 130 K=2,NR1
         IF (H(K,L).GT.10000.) GO TO 130
         IF (ICFAQ.LE.0) GO TO 110
         IF (HT(K,L).LE.G(K,L)) GO TO 110
         STP=((G(K,L)-Z(K,L))*S(K,L)+(HT(K,L)-G(K,L))*SC(K,L))*DX(K,L)*D
     1   Y(K,L)/43560.
         GO TO 120
  110    STP=(HT(K,L)-Z(K,L))*DX(K,L)*DY(K,L)*S(K,L)/43560.
  120    STT=STT+STP
```

```
      IF (L.LT.LCIW) GO TO 130
      IF (L.GT.LCIE) GO TO 130
      IF (K.LT.LCJW) GO TO 130
      IF (K.GT.LCJE) GO TO 130
      STA=STA+STP
  130 CONTINUE
      STOL=STT-STA
C
      RETURN
C
      END
```

# SUBROUTINE CSET

```
      SUBROUTINE CSET (NR,NC,CO,CT,H,G,CS)
C
C     THIS SUBROUTINE SETS THE INITIAL RELATIVE CONCENTRATION IN EACH
C     GRID OF THE AQUIFER.
C
C     CS=INITIAL CODED AQUIFER CONCENTRATION
C     CO=INITIAL (OR CURRENT) UNCODED AQUIFER CONCENTRATION
C     CT=NEW UNCODED AQUIFER CONCENTRATION
C
      DIMENSION CO(NR,NC), CT(NR,NC),H(NR,NC),G(NR,NC),CS(NR,NC)
      DO 100 J=1,NC
      DO 100 I=1,NR
      CT(I,J)=0.0
      IF(CS(I,J).GT.2.0) GO TO 10
      CO(I,J)=CS(I,J)
      GO TO 100
   10 CO(I,J)=CS(I,J)-2.0
  100 CONTINUE
      RETURN
      END
```

# SUBROUTINE QFIX

```
      SUBROUTINE QFIX (NR,NC,DX,DY,CA,H,Z,HT,I,Q,NW,NP,PHR,WELL,PIT,YPT,
     1YAW,YPR,YPM,RPUM,CPM,YRC,RCHR,INYR,HL,TL,FKL,G,PHRTMP,CPPT,OAPW,QR
     2CHR,QPHR,QPUM,QLEAK,AREA,TAREA)
C
C
C     THIS SUBROUTINE COMPUTES THE HYDROLOGIC AND ARTIFICIAL INPUTS.
C       PPT=PRECIPITATION (INCHES/YEAR)
C       CPT=COEF. OF EFFECTIVE PRECIPITATION TO GROUNDWATER (DECIMAL)
C       YPT=DISTRIBUTION OF PRECIPITATION FOR EACH DT OF ONE YEAR
C         (DECIMAL)
C       APW=APPLIED WATER AS A RESULT OF SURFACE IRRIGATION (FEET/YEAR)
C       CAW=COEF. OF DEEP PERCOLATION OF APPLIED WATER (DECIMAL)
C       YAW=DISTRIBUTION OF APPLIED WATER FOR EACH DT OF ONE YEAR
C         (DECIMAL)
C       NGPU=NUMBER OF GRIDS WITH PHREATOPHYTE USE
C       PHR=WATER USED BY PHREATOPHYTES (AF/YEAR).  THIS MAY BE
C           CALCULATED FROM THE ET SUBPROGRAM BY CODING PHR VALUES
C           LESS THAN ZERO.
C       YPR=DISTRIBUTION OF PHREATOPHYTE USE FOR EACH DT OF ONE YEAR
C         (DECIMAL)
C       WELL=WELL NUMBER CODE
C       RPUM=AMOUNT EACH WELL PUMPS PER YEAR (AF/YEAR)
C       CPM=COEF. OF GROUNDWATER REMOVED BY PUMPING (DECIMAL)
C       YPM=DISTRIBUTION OF PUMPING FOR EACH DT OF ONE YEAR (DECIMAL)
C       PIT=RECHARGE PIT NUMBER CODE
C       RCHR=AMOUNT EACH PIT RECHARGES PER YEAR (FEET)
C       YRC=DISTRIBUTION OF PIT RECHARGE FOR EACH DT OF ONE YEAR
C           (DECIMAL)
C       Q=NET VALUE OF HYDROLOGIC AND ARTIFICIAL INPUT PER GRID (AF/DAY)
```

```
C        SQT=TOTAL Q PER DT (AF)
C        SQA=TOTAL Q PER DT BETWEEN STATIONS (AF)
C        REPEAT=DATA INPUT CODE FOR MULTIPLE YEAR ANALYSIS
C
      DIMENSION DX(NR,NC), DY(NR,NC), CA(NR,NC), H(NR,NC), Z(NR,NC), HT(
     1NR,NC), Q(NR,NC), PHR(NR,NC), WELL(NR,NC), PIT(NR,NC), YPT(INYR),
     2YAW(INYR), YPR(INYR), YPM(NW,INYR), RPUM(NW), CPM(NW), YRC(NP,INYR
     3), RCHR(NP), HL(NR,NC), TL(NR,NC), FKL(NR,NC), G(NR,NC), PHRTMP(NR
     4,NC),QPPT(NR,NC), QAPW(NR,NC), QRCHR(NR,NC), QPHR(NR,NC), QLEAK(NR
     5,NC), QPUM(NR,NC), AREA(NR,NC)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJF,LCJW,FWTOP
      COMMON /BLK2/ STA,STOL,STT,SQA,SQT,SQFA,SQBA,SQRT,SQBT,CVA,OVT
C
      IF (I.NE.1) GO TO 320
      ICT=0
      INDX=1
  110 DO 120 K=1,NR
      DO 120 L=1,NC
         PHR(K,L)=0.0
         Q(K,L)=0.0
         PHRTMP(K,L)=0.0
         WELL(K,L)=0.0
         PIT(K,L)=0.0
  120 CONTINUE
      ETCNT=0.0
      DO 130 K=1,INYR
         YPT(K)=0.0
         YAW(K)=0.0
         YPR(K)=0.0
  130 CONTINUE
      FFT=HT(I,J)-G(I,J)
      READ (5,470) PPT,CPT
      IF (PPT.LE.0.0) GO TO 140
      READ (5,480) (YPT(K),K=1,INYR)
  140 READ (5,470) APW,CAW
      IF (APW.LE.0.0) GO TO 150
      READ (5,480) (YAW(K),K=1,INYR)
  150 CONTINUE
      READ (5,490) NGPU
      IF (NGPU.EQ.0) GO TO 170
      DO 160 NPR=1,NGPU
         READ (5,490) J,K,P
         PHR(J,K)=P
  160 CONTINUE
      GO TO 180
  170 IF (SIGN(1.0,NGPU).GT.0.0) GO TO 210
      READ (5,470) PHR
  180 DO 190 KK=1,NR
      DO 190 LL=1,NC
         IF (PHR(KK,LL).LT.0.0) GO TO 210
         IF (PHR(KK,LL).GT.0.0) GO TO 200
  190 CONTINUE
  200 READ (5,480) (YPR(K),K=1,INYR)
  210 IF (NW.LE.0) GO TO 250
      READ (5,490) NW
      DO 220 K=1,NW
      DO 220 L=1,INYR
         YPM(K,L)=0.0
  220 CONTINUE
      DO 240 J=1,NW
         READ (5,500) IWNO,K,L,RPUM(J),CPM(J)
         WELL(K,L)=IWNO
         READ (5,480) (YPM(IWNO,K),K=1,INYR)
         IF (YPM(J,1).NE.0.0) GO TO 240
         IF (SIGN(1.0,YPM(J,1)).GE.0.0) GO TO 240
         DO 230 K=1,INYR
  230    YPM(J,K)=YPM(J-1,K)
  240 CONTINUE
  250 IF (NP.LE.0) GO TO 290
      READ (5,490) NP
      DO 260 K=1,NP
      DO 260 L=1,INYR
         YRC(K,L)=0.0
  260 CONTINUE
      DO 280 J=1,NP
         READ (5,500) IPNO,K,L,RCHR(J)
         PIT(K,L)=IPNO
         READ (5,480) (YRC(IPNO,K),K=1,INYR)
         IF (YRC(J,1).NE.0.0) GO TO 280
         IF (SIGN(1.0,YRC(J,1)).GE.0.0) GO TO 280
```

```
      DO 270 K=1,INYR
  270 YRC(J,K)=YRC(J-1,K)
  280 CONTINUE
  290 CONTINUE
      WRITE (6,510)
      CALL MATROP (NR,NC,CA)
      WRITE (6,620) APW
      WRITE (6,630) (YAW(K),K=1,INYR)
      WRITE (6,560)
      CALL MATROP (NR,NC,PHR)
      WRITE (6,630) (YPR(K),K=1,INYR)
      WRITE (6,640) PPT
      WRITE (6,630) (YPT(K),K=1,INYR)
      IF (NW.LE.0) GO TO 300
      WRITE (6,520)
      CALL MATROP (NR,NC,WELL)
      WRITE (6,650)
      DO 295 J=1,NW
  295 WRITE(6,660)J,RPUM(J),(YPM(J,K),K=1,INYR)
  300 IF (NP.LE.0) GO TO 310
      WRITE (6,530)
      CALL MATROP (NR,NC,PIT)
      WRITE (6,670)
      DO 305 J=1,NP
  305 WRITE(6,680)J,RCHR(J),(YRC(J,K),K=1,INYR)
C
  310 IF (I.NE.1) GO TO 320
      WRITE (6,590)
      CALL MATROP (NR,NC,H)
      WRITE (6,600) STA,STOL,STT
C
  320 ICT=ICT+1
      IF (ICT.LE.INYR) GO TO 330
      ICT=ICT-INYR-1
      READ (5,470) REPEAT
      IF (REPEAT.NE.0.0) GO TO 320
      KYEAR=I/INYR
      WRITE (6,610) KYEAR
      GO TO 110
  330 PCNT=INDX
      FI=I
      SQA=0.0
      SQT=0.0
      KCT=0
      DO 440 K=1,NR
      DO 440 L=1,NC
        IF (H(K,L).GT.1.E4) GO TO 440
        IF (HT(K,L).GT.Z(K,L)) GO TO 350
        A=0.0
        IF (KCT.GT.0) GO TO 340
        WRITE (6,580) I
        KCT=1
  340   WRITE (6,540) K,L
        GO TO 360
  350   A=1.0
  360   CONTINUE
C
      QPPT(K,L)=(PPT*CPT*YPT(ICT)*AREA(K,L)/TAREA)/(12.*43560.)
      QAPW(K,L)=(APW*CAW*CA(K,L)*YAW(ICT)*AREA(K,L)/TAREA)/43560.
        JJJ=PIT(K,L)
        IF (JJJ.LE.0) GO TO 370
      QRCHR(K,L)=RCHR(JJJ)*YRC(JJJ,ICT)*AREA(K,L)/43560.
        GO TO 380
  370 QRCHR(K,L)=0.0
  380   CONTINUE
        IF (PHR(K,L).GE.0.0) GO TO 390
     \ QPHR(K,L)=ET(HT(K,L),G(K,L),K,L)*AREA(K,L)/43560.
      PHRTMP(K,L)=QPHR(K,L)
        ETCNT=1.
        GO TO 400
  390 QPHR(K,L)=PHR(K,L)*YPR(ICT)
  400   CONTINUE
        JJ=WELL(K,L)
        IF (JJ.LE.0) GO TO 410
      QPUM(K,L)=RPUM(JJ)*YPM(JJ,ICT)*CPM(JJ)

        GO TO 420
  410 QPUM(K,L)=0.0
  420   CONTINUE
        IF (ILKAQ.LE.0) GO TO 430
        QLEAK(K,L)=FKL(K,L)*(HT(K,L)-HL(K,L))*AREA(K,L)*DT/(TL(K,L)*435
     160.)
        GO TO 431
```

```
430     GLEAK(K,L)=0.0
431     Q(K,L)=(QPPT(K,L)+QAPW(K,L)+QRCHP(K,L)-QPHR(K,L)-QPUM(K,L)-QLEA
       1K(K,L))/DT
C
        SQT=SQT+Q(K,L)*DT
        IF (L.LT.LCIW) GO TO 440
        IF (L.GT.LCIE) GO TO 440
        IF (K.LT.LCJW) GO TO 440
        IF (K.GT.LCJE) GO TO 440
        SQA=SQA+Q(K,L)*DT
  440 CONTINUE
      IF ((FI*DT).NE.(PCNT*FWTOP)) GO TO 460
      INDX=INDX+1
      IF (ETCNT.LE.0.) GO TO 450
      WRITE (6,570)
      CALL MATROP (NR,NC,PHRTMP)
  450 WRITE (6,550) I
      CALL MATROP (NR,NC,Q)
  460 RETURN
C
  470 FORMAT (8F10.1)
  480 FORMAT (16F5.1)
  490 FORMAT (2I5,7F10.1)
  500 FORMAT (3I5,6F10.1)
  510 FORMAT (1H1,45X,40HCOEFFICIENT FOR PART OF BLOCK IRRIGATED./)
  520 FORMAT (1H1,57X,16HWELL NUMBER MAP./)
  530 FORMAT (1H1,53X,24HRECHARGE PIT NUMBER MAP./)
  540 FORMAT (31H WITHDRAWAL RESTRICTED IN GRID 2I3)
  550 FORMAT (1H1,30X, 49HMATRIX OF Q(I,J) (AC-FT/DAY) FOR INCREMENT NUM
     1BER,I10)
  560 FORMAT (1H1,20X,60HMATRIX OF PHR(I,J) - (ACRE-FEET OF WATER USED /
     1 GRID / YEAR))
  570 FORMAT (1H1,20X,60HMATRIX OF PHR(I,J) - (ACRE-FEET OF WATER USED /
     1 GRID / INYR))
  580 FORMAT (1H1,94HWATER TABLE AND BEDROCK ELEVATIONS PREVENT WITHDRAW
     1AL FROM THE FOLLOWING GRIDS FOR TIME PERIOD,I5)
  590 FORMAT (1H1,37X, 46HINITIAL HEAD ELEVATION MAP  (FEET ABOVE DATUM)
     1,/)
  600 FORMAT (1H ,///,48X, 24HINITIAL STORAGE  (AC-FT),//,10X,  5HSTA= ,
     1F15.3,10X,  6HSTOL= ,F15.3,10X,  5HSTT= ,F15.3)
  610 FORMAT (1H1,/////,55X,  4HYEAR,1X,I3,2X, 11HOF ANALYSIS)
  620 FORMAT (1H ,///,38X, 21HYEARLY APPLIED WATER=,F10.3,5X,  9HFEET/YE
     1AR)
  630 FORMAT (1H ,//,5X, 12HDISTRIBUTION,3X,12F7.4)
  640 FORMAT (1H1,///,37X, 21HYEARLY PRECIPITATION=,F10.3,5X, 11HINCHES/
     1YEAR)
  650 FORMAT (1H1,/////,60X, 10HWELL TABLE)
  660 FORMAT (1H ,////,5X,  8HWELL NO.,7X,I10,//,5X, 17HRATE (AC-FT/YEAR
     1),6X,F10.4,(/,5X, 12HDISTRIBUTION,3X,12F7.4))
  670 FORMAT (1H1,/////,53X, 14HRECHARGE TABLE)
  680 FORMAT (1H ,////,5X,  7HPIT NO.,8X,I10,//,5X, 16HRATE (FEET/YEAR),
     14X,F10.4,(/,5X, 12HDISTRIBUTION,3X,12F7.4))
C
      END
```

# FUNCTION ET

```
      FUNCTION ET(AHT,AG,K,L)
C
C
C     THIS SUBPROGRAM COMPUTES THE PHREATOPHYTE USE USING WATER TABLE
C       ELEVATIONS.
C       ET=EVAPOTRANSPIRATION (FEET/INYR)
C       DTWT=DEPTH TO WATER TABLE FROM GROUND SURFACE (FEET)
C
      DTWT=AG-AHT
      IF (DTWT.GE.0.0) GO TO 110
      WRITE (6,120) K,L
  110 CONTINUE
      ET=-0.0
      RETURN
C
  120 FORMAT (1H1,/////,45X, 37HET ERROR, DTWT LESS THAN ZERO IN GRID,2I
     15)
C
      END
```

# SUBROUTINE MATSOL

```
      SUBROUTINE MATSOL (NOROW,NOCOL,IP,IR,FK,PHI,H,HT,Z,DELX,DELY,Q,CMA
     1TRX,CR,A,B,G,PHIC,HP,HF)
C
C
C     THIS SUBROUTINE SETS UP THE COEFFICIENT MATRIX AND RIGHT HAND
C       SIDE VECTOR MATRIX.
C       CMATRX=COEFFICIENT MATRIX
C       CR=RIGHT HAND SIDE VECTOR MATRIX
C
      DIMENSION FK(NOROW,NOCOL), PHI(NOROW,NOCOL), H(NOROW,NOCOL), HT(NO
     1ROW,NOCOL), Z(NOROW,NOCOL), DELX(NOROW,NOCOL), DELY(NOROW,NOCOL),
     2Q(NOROW,NOCOL), CMATRX(IP,IR), CR(IP), A(NOROW,NOCOL), B(NOROW,NOC
     3OL), G(NOROW,NOCOL), PHIC(NOROW,NOCOL), HP(NOROW,NOCOL), HF(NOROW,
     4NOCOL)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FWTOP
C
      DELT=DT
      DO 110 J=1,IR
      DO 110 I=1,IP
         CMATRX(I,J)=0.0
  110 CONTINUE
      DO 120 I=1,NOROW
      DO 120 J=1,NOCOL
         A(I,J)=0.0
         B(I,J)=0.0
  120 CONTINUE
      NT=0
      NC1=NOCOL-1
      NR1=NOROW-1
      IB=NOROW-2
      IM=IB+1
      IC=IM+1
      ID=2*IB+1
      DO 160 J=2,NC1
      DO 160 I=2,NR1
         NT=NT+1
         CR(NT)=0.0
         IF (H(I,J).GE.10000.0) GO TO 150
         JA=I
         JD=I
C
C                       LEFT(A)
C
         CMATRX(NT,1)=PARAM(FK(JA,J-1),FK(I,J),HT(JA,J-1),HT(I,J),Z(JA,J
     1   -1),Z(I,J),DELX(JA,J-1),DELX(I,J),DELY(JA,J-1),DELY(I,J),G(JA,J
     2   -1),G(I,J))
C
C                       TOP(B)
C
         CMATRX(NT,IB)=PARAM(FK(I-1,J),FK(I,J),HT(I-1,J),HT(I,J),Z(I-1,J
     1   ),Z(I,J),DELY(I-1,J),DELY(I,J),DELX(I-1,J),DELX(I,J),G(I-1,J),G
     2   (I,J))
C
C                       BOTTOM(C)
C
         CMATRX(NT,IC)=PARAM(FK(I+1,J),FK(I,J),HT(I+1,J),HT(I,J),Z(I+1,J
     1   ),Z(I,J),DELY(I+1,J),DELY(I,J),DELX(I+1,J),DELX(I,J),G(I+1,J),G
     2   (I,J))
         A(I,J)=CMATRX(NT,IC)
C
C                       RIGHT(D)
C
         CMATRX(NT,ID)=PARAM(FK(JD,J+1),FK(I,J),HT(JD,J+1),HT(I,J),Z(JD,
     1   J+1),Z(I,J),DELX(JD,J+1),DELX(I,J),DELY(JD,J+1),DELY(I,J),G(JD,
     2   J+1),G(I,J))
         B(I,J)=CMATRX(NT,ID)
C
         CALL NSCONT (H(JA,J-1),HT(JA,J-1),HT(I,J),Z(JA,J-1),Z(I,J),CMAT
     1   RX(NT,1),CMATRX(NT,IM),CR(NT))
         CALL NSCONT (H(I-1,J),HT(I-1,J),HT(I,J),Z(I-1,J),Z(I,J),CMATRX(
     1   NT,IB),CMATRX(NT,IM),CR(NT))
         CALL NSCONT (H(I+1,J),HT(I+1,J),HT(I,J),Z(I+1,J),Z(I,J),CMATRX(
     1   NT,IC),CMATRX(NT,IM),CR(NT))
         CALL NSCONT (H(JD,J+1),HT(JD,J+1),HT(I,J),Z(JD,J+1),Z(I,J),CMAT
     1   RX(NT,ID),CMATRX(NT,IM),CR(NT))
C
C                       (E)
C
```

```
      IF (ICFAQ.LE.0) GO TO 130
      IF (HT(I,J).LE.G(I,J)) GO TO 130
      STCOEF=PHIC(I,J)
      GO TO 140
  130 STCOEF=PHI(I,J)
  140 CONTINUE
      CMATRX(NT,IM)=CMATRX(NT,IM)-(CMATRX(NT,1)+CMATRX(NT,IB)+CMATRX(
     1 NT,IC)+CMATRX(NT,ID)+(STCOEF*DELX(I,J)*DELY(I,J))/DELT)
      CR(NT)=CR(NT)-(HT(I,J)*STCOEF*DELX(I,J)*DELY(I,J))/DELT-Q(I,J)*
     1 43560.0
C
      GO TO 160
  150 CMATRX(NT,IM)=1.0
      CR(NT)=HT(I,J)
  160 CONTINUE
      REWIND 7
      WRITE (7) CMATRX,CR
      CALL BSOLVE (CMATRX,IP,IR,CR)
      NT=0
      DO 170 J=2,NC1
      DO 170 I=2,NR1
         NT=NT+1
         HT(I,J)=CR(NT)
         HF(I,J)=CR(NT)
  170 CONTINUE
      IF (ICFAQ.LE.0) GO TO 230
      REWIND 7
      READ (7) CMATRX,CR
      ICAC=0
      NT=0
      DO 210 J=2,NC1
      DO 210 I=2,NR1
         NT=NT+1
         IF (HT(I,J).LE.G(I,J)) GO TO 180
         IF (HP(I,J)-G(I,J)) 190,190,210
  180    IF (HP(I,J)-G(I,J)) 210,210,200
  190 ERROR=(G(I,J)*(PHI(I,J)-PHIC(I,J)))*DELX(I,J)*DELY(I,J)/DELT
         CR(NT)=CR(NT)+ERROR
         CMATRX(NT,NR1)=CMATRX(NT,NR1)+(PHI(I,J)-PHIC(I,J))*DELX(I,J)*DE
     1   LY(I,J)/DELT
         WRITE (6,240) I,J
         ICAC=1
         GO TO 210
  200 ERROR=(G(I,J)*(PHI(I,J)-PHIC(I,J)))*DELX(I,J)*DELY(I,J)/DELT
         CR(NT)=CR(NT)-ERROR
         CMATRX(NT,NR1)=CMATRX(NT,NR1)+(PHIC(I,J)-PHI(I,J))*DELX(I,J)*DE
     1   LY(I,J)/DELT
         WRITE (6,250) I,J
         ICAC=1
  210 CONTINUE
      IF (ICAC.EQ.0) GO TO 230
      CALL BSOLVE (CMATRX,IP,IR,CR)
      NT=0
      DO 220 J=2,NC1
      DO 220 I=2,NR1
         NT=NT+1
         HT(I,J)=CR(NT)
         HF(I,J)=CR(NT)
  220 CONTINUE
  230 RETURN
C
  240 FORMAT (1H ,43X,  4HGRID,2I5,5X, 22HUNCONFINED TO CONFINED)
  250 FORMAT (1H ,43X,  4HGRID,2I5,5X, 22HCONFINED TO UNCONFINED)
C
      END
```

# FUNCTION PARAM

```
      FUNCTION PARAM(AK1,AK2,AHT1,AHT2,AZ1,AZ2,AX1,AX2,AY1,AY2,AG1,AG2)
C
C
C     THIS SUBPROGRAM COMPUTES THE COEFFICIENTS USED IN MATSOL AND
C       BYFLOW.  IT IS APPLICABLE TO CASES OF VARIABLE DX, DY, FK,
C       AND SATURATED THICKNESS.
C
```

```
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FKTOP
C
      IF (ICFAQ.LE.0) GO TO 110
      A=AMIN1(AHT1,AG1)
      B=AMIN1(AHT2,AG2)
      SATHCK=AMAX1(A,B)-AMAX1(AZ1,AZ2)
      GO TO 120
  110 SATHCK=AMAX1(AHT1,AHT2)-AMAX1(AZ1,AZ2)
  120 PARAM=(2.*AK1*AK2*AY1*AY2*SATHCK)/((AX1*AK2*AY2)+(AX2*AK1*AY1))
C
      RETURN
C
      END
```

# SUBROUTINE NSCONT

```
      SUBROUTINE NSCONT (HA,HTA,HTM,ZA,ZM,CRXA,CRXM,CRL)
C
C
C     THIS SUBROUTINE TRANSFERS THE COEFFICIENTS, MULTIPLIED BY THEIR
C       RESPECTIVE H-VALUE, TO THE RIGHT HAND SIDE VECTOR MATRIX IN
C       CASE OF ADJACENT CONSTANT HEAD OR KNOWN BOUNDARY CONDITIONS.
C       IT ALSO SETS COEFFICIENTS EQUAL TO ZERO IN CASE OF ADJACENT
C       IMPERMEABLE BOUNDARIES.
C
      IF (HA.LT.20000.0) GO TO 110
      CRL=CRL-CRXA*HTA
      CRXM=CRXM-CRXA
      CRXA=0.0
      GO TO 120
  110 IF (HA.GE.10000.0) GO TO 130
  120 IF ((HTM-ZM).LE.1.0.AND.HTM.GT.HTA) GO TO 130
      IF ((HTA-ZA).GT.1.0.OR.HTA.LE.HTM) GO TO 140
  130 CRXA=0.0
C
  140 RETURN
C
      END
```

# SUBROUTINE BSOLVE

```
      SUBROUTINE BSOLVE (D,N,M,V)
C
C
C     THIS SUBROUTINE SOLVES THE MATRIX, SET UP IN MATSOL, BY GAUSS
C       ELIMINATION.
C
      DIMENSION D(N,M), V(N)
C
      LR=(M-1)/2
      DO 120 L=1,LR
         IM=LR-L+1
      DO 120 I=1,IM
         DO 110 J=2,M
  110    D(L,J-1)=D(L,J)
         KN=N-L
         KM=M-I
         D(L,M)=0.0
  120 D(KN+1,KM+1)=0.0
      LR=LR+1
      IM=N-1
      DO 190 I=1,IM
         NPIV=I
         LS=I+1
         DO 130 L=LS,LR
            IF (ABS(D(L,1)).GT.ABS(D(NPIV,1))) NPIV=L
  130    CONTINUE
```

```
      IF (NPIV.LE.I) GO TO 150
      DO 140 J=1,M
         TEMP=D(I,J)
         D(I,J)=D(NPIV,J)
  140 D(NPIV,J)=TEMP
      TEMP=V(I)
      V(I)=V(NPIV)
      V(NPIV)=TEMP
  150 V(I)=V(I)/D(I,1)
      DO 160 J=2,M
  160 D(I,J)=D(I,J)/D(I,1)
      DO 180 L=LS,LR
         TEMP=D(L,1)
         V(L)=V(L)-TEMP*V(I)
         DO 170 J=2,M
  170    D(L,J-1)=D(L,J)-TEMP*D(I,J)
  180 D(L,M)=0.0
      IF (LR.LT.N) LR=LR+1
  190 CONTINUE
      V(N)=V(N)/D(N,1)
      JM=2
      DO 210 I=1,IM
         L=N-I
         DO 200 J=2,JM
            KM=L+J
  200    V(L)=V(L)-D(L,J)*V(KM-1)
         IF (JM.LT.M) JM=JM+1
  210 CONTINUE
C
      RETURN
C
      END
```

# SUBROUTINE BJUST

```
      SUBROUTINE BJUST (NR,NC,H,HT,HP,DX,DY,I)
C
C
C     THIS SUBROUTINE ADJUSTS THE UNDERFLOW BOUNDARY WATER TABLE OR
C       HEAD ELEVATIONS.  BOUNDARY ELEVATIONS ARE HELD CONSTANT FOR
C       ODD TIME STEPS.  GRADIENTS ARE COMPUTED THREE GRIDS IN AND
C       PROJECTED BACK TO OBTAIN NEW WATER LEVEL ELEVATIONS OR
C       HEAD ELEVATIONS AT BOUNDARIES.
C
      DIMENSION H(NR,NC), HT(NR,NC), HP(NR,NC), DX(NR,NC), DY(NR,NC)
C
      IF ((I/2*2).NE.I) RETURN
C
      NR1=NR-1
      NC1=NC-1
C
      DO 120 I2=2,NC1
         IF (H(1,I2).GE.30000.0) GO TO 110
         IF (H(1,I2).LT.20000.0) GO TO 110
         DITP=(HT(2,I2)-HT(3,I2))*(DY(1,I2)+DY(2,I2))/(DY(2,I2)+DY(3,I2)
     1   )
         HT(1,I2)=HT(2,I2)+DITP
  110    IF (H(NR,I2).GE.30000.0) GO TO 120
         IF (H(NR,I2).LT.20000.0) GO TO 120
         DIBT=(HT(NR-2,I2)-HT(NR-3,I2))*(DY(NR,I2)+DY(NR-1,I2))/(DY(NR-2
     1   ,I2)+DY(NR-1,I2))
         HT(NR,I2)=HT(NR1,I2)-DIBT
  120 CONTINUE
C
      DO 140 I1=2,NR1
         IF (H(I1,1).GE.30000.0) GO TO 130
         IF (H(I1,1).LT.20000.0) GO TO 130
         DILT=(HT(I1,2)-HT(I1,3))*(DX(I1,1)+DX(I1,2))/(DX(I1,2)+DX(I1,3)
     1   )
         HT(I1,1)=HT(I1,2)+DILT
  130    IF (H(I1,NC).GE.30000.0) GO TO 140
         IF (H(I1,NC).LT.20000.0) GO TO 140
         DIRT=(HT(I1,NC-2)-HT(I1,NC-1))*(DX(I1,NC)+DX(I1,NC-1))/(DX(I1,N
     1   C-2)+DX(I1,NC-1))
         HT(I1,NC)=HT(I1,NC1)-DIRT
  140 CONTINUE
C
      RETURN
C
      END
```

# SUBROUTINE ODFLOD

```
      SUBROUTINE ODFLOD (NR,NC,H,HT,Z,G,S,DX,DY,SC)
C
C
C     THIS SUBROUTINE CHECKS FOR OVERDRAWN OR FLOODED AREAS.
C       OACFTT=OVT=TOTAL OVERDRAW (AF)
C       FACFTT=FVT=TOTAL AMOUNT FLOODED (AF)
C       OACFTA=OVA=OVERDRAW BETWEEN BUFFER ZONE BOUNDARIES (AF)
C       FACFTA=FVA=AMOUNT FLOODED BETWEEN BUFFER ZONE BOUNDARIES (AF)
C
      DIMENSION H(NR,NC), HT(NR,NC), Z(NR,NC), G(NR,NC), S(NR,NC), DX(NR
     1,NC), DY(NR,NC), SC(NR,NC)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FKTOP
      COMMON /BLK2/ STA,STOL,STT,SQA,SQT,SQRA,SQBA,SQRT,SQBT,CVA,OVT
C
      OACFTT=0.0
      FACFTT=0.0
      OACFTA=0.0
      FACFTA=0.0
      SVOLO=0.0
      SVOLF=0.0
      KCT=0
      DO 180 J=1,NC
      DO 180 I=1,NR
         IF (H(I,J).GE.10000.0) GO TO 180
         IF (HT(I,J).GE.Z(I,J)) GO TO 130
         ODFT=Z(I,J)-HT(I,J)
         FACFT=0.0
         FFT=0.0
         SS=S(I,J)
         IF (ICFAQ.LE.0) GO TO 110
         SS=SC(I,J)
         IF (HT(I,J).LE.G(I,J)) SS=S(I,J)
  110    ODACFT=ODFT*DX(I,J)*DY(I,J)*SS/43560.
         IF (H(I,J).GE.20000.0) GO TO 120
         SVOLO=ODACFT
  120    HT(I,J)=Z(I,J)
         GO TO 150
  130    IF (ICFAQ.GT.0) GO TO 180
         IF (HT(I,J).LE.G(I,J)) GO TO 180
         FACFT=FFT*DX(I,J)*DY(I,J)*S(I,J)/43560.
         ODFT=0.0
         ODACFT=0.0
         SVOLO=0.0
         IF (H(I,J).GT.20000.0) GO TO 140
         SVOLF=FACFT
         GO TO 150
  140    HT(I,J)=G(I,J)
         SVOLF=0.0
  150    OACFTT=OACFTT+SVOLO
         FACFTT=FACFTT+SVOLF
         IF (J.LT.LCIW) GO TO 160
         IF (J.GT.LCIE) GO TO 160
         IF (I.LT.LCJW) GO TO 160
         IF (I.GT.LCJE) GO TO 160
         OACFTA=OACFTA+SVOLO
         FACFTA=FACFTA+SVOLF
  160    IF (KCT.GT.0) GO TO 170
         WRITE (6,200)
         WRITE (6,210)
         KCT=1
  170    WRITE (6,220) I,J,ODFT,ODACFT,FFT,FACFT
  180 CONTINUE
      IF (OACFTT.EQ.0.0.AND.FACFTT.EQ.0.0) GO TO 190
      WRITE (6,230) OACFTT,FACFTT,OACFTA,FACFTA
  190 OVA=OACFTA
      OVT=OACFTT
      RETURN
C
  200 FORMAT (1H1,14H-ROW - COL NR.,6X,15HO V E R D R A W,2X,13HF L O O
     1D E D,5X,8HAREA OD.,4X,8HAREA FD./)
  210 FORMAT (1H ,18X,2(5X,11HFT       ACFT),6X,4HACFT,8X,4HACFT/)
  220 FORMAT (3H    2I4,9X,4F8.2)
  230 FORMAT (12H0T O T A L S,8X,2(8X,F8.2),2X,F8.2,4X,F8.2//)
C
      END
```

# SUBROUTINE BYFLOW

```
      SUBROUTINE BYFLOW (NR,NC,NA,NB,FK,H,HF,Z,DX,DY,SQGGI,SQGGJ,SQR,CMA
     1TRX,A,B,HP,G,ITIME,CO,CT,PHI,PHIC,CS,CPPT,QAPW,CRCHR,CPHR,QPUM,CLE
     2AK,CPPT,CAPW,CRCHR,CSQR, Q,CPUM,CLEAK,CPHR)
C
C
C     THIS SUBROUTINE COMPUTES FLOWS FOR EACH GRIC.. FLOW THROUGH
C       BOUNDARIES AND FROM CONSTANT HEAD GRIDS IS CALCULATED.
C     THIS SUBROUTINE COMPUTES NEW RELATIVE CONCENTRATIONS FOR EACH GRID
C     BASED ON ALL INPUT AND OUTPUT VARIABLES TO EACH GRID.
C
C       SQGGI=FLOW BETWEEN GRIDS IN I-DIRECTION (AF)
C       SQGGJ=FLOW BETWEEN GRIDS IN J-DIRECTION (AF)
C       SQBT=TOTAL INFLOW THROUGH BOUNDARIES (AF)
C       SQBA=INFLOW THROUGH BUFFER ZONE BOUNDARIES (AF)
C       SQR=INFLOW FROM CONSTANT HEAD GRIDS
C       SQRT=TOTAL INFLOW FROM RIVER OR CONSTANT HEAD GRIDS (AF)
C       SQRA=INFLOW FROM RIVER OR CONSTANT HEAD GRIDS WITHIN BUFFER
C            ZONE BOUNDARIES (AF)
C
      DIMENSION FK(NR,NC), H(NR,NC), HF(NR,NC), Z(NR,NC), DX(NR,NC), DY(
     1NR,NC), SQGGI(NR,NC), SQGGJ(NR,NC), SQR(NR,NC), CMATRX(NA,NB), A(N
     2R,NC),B(NR,NC),HP(NR,NC), G(NR,NC),CO(NR,NC),CT(NR,NC),PHI(NR,NC)
     3,PHIC(NR,NC),CS(NR,NC),QPPT(NR,NC),QAPW(NR,NC),CRCHR(NR,NC),CPHR(
     4NR,NC),QPUM(NR,NC),QLEAK(NR,NC),Q(NR,NC),CPUM(NR,NC),CLEAK(NR,NC),
     5CPHR(NR,NC),CPPT(NR,NC),CAPW(NR,NC),CRCHR(NR,NC),CSQR(NR,NC)
C
      COMMON /BLK1/ DT,ST,ICFAQ,ILKAQ,LCIE,LCIW,LCJE,LCJW,FWTOP
      COMMON /BLK2/ STA,STOL,STT,SQA,SQT,SQRA,SQBA,SQRT,SQBT,OVA,OVT
C
      LS=LCIE
      LN=LCIW-1
      NS=LCJE
      NN=LCJW-1
      NR1=NR-1
      NC1=NC-1
      SQBIA=0
      SQBJA=0
      TQBIA=0.0
      TQBJA=0.0
C
C     DO 20 LOOP COMPUTES FLOW IN THE I DIRECTION
C     STATEMENTS 10 AND 12 FORCES DISCHARGES AT THE FIRST AND LAST
C     GRIDS TO BE COUNTED AS BOUNDARY GRIDS
C     STATEMENT 14 AND 16 COMPUTES RIVER FLOWS.  RIVER MUST BE INTERIOR
C     TO GRIDS 3 AND NR1 OR INTERIOR TO LCIE AND LCIW.
C
      DO 210 J=1,NC
         SQGGI(NR,J)=0.0
      DO 210 I=1,NR1
C
C     CHECK FOR IMPERMEABLE BOUNDARY
C     CHECK FOR ADJACENT CONSTANT HEAD OR CONSTANT GRADIENT CONDITIONS
C
         KK=(H(I,J)/10000.)+1
         KL=(H(I+1,J)/10000.)+1
         GO TO (110,160,120,130), KK
  110    GO TO (140,160,140,140), KL
  120    GO TO (140,160,160,160), KL
  130    GO TO (140,160,160,140), KL
C
  140    IF (A(I,J).NE.0.0) GO TO 150
         SQGGI(I,J)=PARAM(FK(I+1,J),FK(I,J),HP(I+1,J),HP(I,J),Z(I+1,J),Z
     1   (I,J),DY(I+1,J),DY(I,J),DX(I+1,J),DX(I,J),G(I+1,J),G(I,J))*(HF(
     2   I,J)-HF(I+1,J))*DT/43560.
         GO TO 170
  150    SQGGI(I,J)=A(I,J)*(HF(I,J)-HF(I+1,J))*DT/43560.
         GO TO 170
  160    SQGGI(I,J)=0.0
  170    IF (I.NE.1) GO TO 180
         IF (KK.EQ.4) GO TO 190
         SQBI=SQGGI(I,J)
C
C     SUM OF I-FLOW THROUGH BOUNDARIES
C
         SQBIA=SQBIA+SQBI
         GO TO 190
  180    IF (I.NE.NR1) GO TO 190
         IF (KK.EQ.4) GO TO 190
         SQBI=-SQGGI(I,J)
```

```
C
C     SUM OF I-FLOW THROUGH BOUNDARIES
C
         SQBIA=SQBIA+SQBI
  190    IF (I.NE.NN) GO TO 200
         IF (J.LT.LCIW) GO TO 210
         IF (J.GT.LCIE) GO TO 210
         IF (KK.EQ.4) GO TO 210
         TQBI=SQGGI(I,J)
C
C     SUM OF I-FLOW THROUGH BUFFER ZONE BOUNDARIES
C
         TQBIA=TQBIA+TQBI
         GO TO 210
  200    IF (I.NE.NS) GO TO 210
         IF (J.LT.LCIW) GO TO 210
         IF (J.GT.LCIE) GO TO 210
         IF (KK.EQ.4) GO TO 210
         TQBI=-SQGGI(I,J)
C
C     SUM OF I-FLOW THROUGH BUFFER ZONE BOUNDARIES
C
         TQBIA=TQBIA+TQBI
  210 CONTINUE
      WRITE (6,400) ITIME
      CALL MATROP (NR,NC,SQGGI)
C
C     DO 40 LOOP COMPUTES FLOWS IN THE J-DIRECTION.
C
      DO 320 I=1,NR
         SQGGJ(I,NC)=0.0
      DO 320 J=1,NC1
         KK=(H(I,J)/10000.)+1
         KL=(H(I,J+1)/10000.)+1
         GO TO (220,270,230,240), KK
  220    GO TO (250,270,250,250), KL
  230    GO TO (250,270,270,270), KL
  240    GO TO (250,270,270,250), KL
C
  250    IF (B(I,J).NE.0.0) GO TO 260
         SQGGJ(I,J)=PARAM(FK(I,J+1),FK(I,J),HP(I,J+1),HP(I,J),Z(I,J+1),Z
     1   (I,J),DX(I,J+1),DX(I,J),DY(I,J+1),DY(I,J),G(I,J+1),G(I,J))*(HF(
     2   I,J)-HF(I,J+1))*DT/43560.
         GO TO 280
  260    SQGGJ(I,J)=B(I,J)*(HF(I,J)-HF(I,J+1))*DT/43560.
         GO TO 280
  270    SQGGJ(I,J)=0.0
  280    IF (J.NE.1) GO TO 290
         IF (KK.EQ.4) GO TO 300
         SQBJ=SQGGJ(I,J)
C
C     SUM OF J-FLOW THROUGH BOUNDARIES
C
         SQBJA=SQBJA+SQBJ
         GO TO 300
  290    IF (J.NE.NC1) GO TO 300
         IF (KK.EQ.4) GO TO 300
         SQBJ=-SQGGJ(I,J)
C
C     SUM OF J-FLOW THROUGH BOUNDARIES
C
         SQBJA=SQBJA+SQBJ
  300    IF (J.NE.LN) GO TO 310
         IF (I.LT.LCJW) GO TO 320
         IF (I.GT.LCJE) GO TO 320
         IF (KK.EQ.4) GO TO 320
         TQBJ=SQGGJ(I,J)
C
C     SUM OF J-FLOW THROUGH BUFFER ZONE BOUNDARIES
C
         TQBJA=TQBJA+TQBJ
         GO TO 320
  310    IF (J.NE.LS) GO TO 320
         IF (I.LT.LCJW) GO TO 320
         IF (I.GT.LCJE) GO TO 320
         IF (KK.EQ.4) GO TO 320
         TQBJ=-SQGGJ(I,J)
C
C     SUM OF J-FLOW THROUGH BUFFER ZONE BOUNDARIES
C
         TQBJA=TQBJA+TQBJ
  320 CONTINUE
```

```
      WRITE (6,410) ITIME
      CALL MATROP (NR,NC,SQGGJ)
C
C     RELATIVE CONCENTRATION CALCULATIONS
C     CALCULATE CHANGE IN RELATIVE CONCENTRATIONS DUE TO ALL VARIABLES
C     EXCEPT CONSTANT HEAD SOURCES INSIDE THE BOUNDARY GRIDS.
C     SOURCE GRIDS ARE TAKEN AS C=1.0
      DO 10 J=1,NC
      DO 10 I=1,NR
      CPUM(I,J)=CO(I,J)
      CLEAK(I,J)=CO(I,J)
      CPHR(I,J)=0.0
   10 CONTINUE
      DO 530 J=2,NC1
      DO 530 I=2,NR1
      IF (CS(I,J) .GT. 2.0) GO TO 530
      IF (HP(I,J) .GT. G(I,J)) GO TO 480
      CT(I,J)=CO(I,J-1)*SQGGJ(I,J-1)+CO(I-1,J)*SQGGI(I-1,J)-CO(I,J)*(
     1SQGGI(I,J)+SQGGJ(I,J))+QPPT(I,J)*CPPT(I,J)+QRCHR(I,J)*CRCHR(I,J)+
     2QAPW(I,J)*CAPW(I,J)-QPUM(I,J)*CPUM(I,J)-CPHR(I,J)*CPHR(I,J)-CLEAK(
     3I,J)*CLEAK(I,J)
      GO TO 490
  480 CT(I,J)=CO(I,J-1)*SQGGJ(I,J-1)+CO(I-1,J)*SQGGI(I-1,J)-CO(I,J)*(
     1SQGGI(I,J)+SQGGJ(I,J))-QPUM(I,J)*CPUM(I,J)
  490 IF(SQGGI(I-1,J).GE.0.0) GO TO 500
      CT(I,J)=CT(I,J)+(CO(I,J)-CO(I-1,J))*SQGGI(I-1,J)
  500 IF(SQGGI(I,J).GE.0.0) GO TO 510
      CT(I,J)=CT(I,J)-(CO(I+1,J)-CO(I,J))*SQGGI(I,J)
  510 IF(SQGGJ(I,J-1).GE.0.0) GO TO 520
      CT(I,J)=CT(I,J)+(CO(I,J)-CO(I,J-1))*SQGGJ(I,J-1)
  520 IF(SQGGJ(I,J).GE.0.0) GO TO 530
      CT(I,J)=CT(I,J)-(CO(I,J+1)-CO(I,J))*SQGGJ(I,J)
  530 CONTINUE
C
      SQRT=0.0
      DO 330 J=1,NC
         SQGGI(1,J)=0.0
         SQGGI(NR1,J)=0.0
  330 CONTINUE
      DO 340 I=1,NR
         SQGGJ(I,1)=0.0
         SQGGJ(I,NC1)=0.0
  340 CONTINUE
      DO 350 I=2,NR1
      DO 350 J=2,NC1
         SQR(I,J)=0.0
         KK=(H(I,J)/10000.)+1
         IF (KK.NE.4) GO TO 350
         SQR(I,J)=-SQGGI(I-1,J)+SQGGI(I,J)-SQGGJ(I,J-1)+SQGGJ(I,J)
         SQRL=SQR(I,J)
C
C     TOTAL INFLOW FROM CONSTANT HEAD GRIDS
C
         SQRT=SQRT+SQRL
  350 CONTINUE
C
C     TOTAL INFLOW THROUGH BOUNDARIES
C
      SQBT=SQBJA+SQBIA
      IF (SQRT.LE.0.0) GO TO 360
      WRITE (6,420) ITIME
      CALL MATROP (NR,NC,SQR)
C
C
  360 SQRA=0.0
      DO 370 J=LCIW,LCIE
         SQGGI(NN,J)=0.0
         SQGGI(NS,J)=0.0
  370 CONTINUE
      DO 380 I=LCJW,LCJE
         SQGGJ(I,LN)=0.0
         SQGGJ(I,LS)=0.0
  380 CONTINUE
      DO 390 I=LCJW,LCJE
      DO 390 J=LCIW,LCIE
         SQR(I,J)=0.0
         KK=(H(I,J)/10000.)+1
         IF (KK.NE.4) GO TO 390
         SQR(I,J)=-SQGGI(I-1,J)+SQGGI(I,J)-SQGGJ(I,J-1)+SQGGJ(I,J)
         SQRL=SQR(I,J)
C
C     TOTAL INFLOW FROM CONSTANT GRIDS WITHIN BUFFER ZONE BOUNDARIES
C
```

```
      SQRA=SQRA+SQRL
  390 CONTINUE
C
C     TOTAL INFLOW THROUGH BUFFER ZONE BOUNDARIES
C
      SQBA=TQBJA+TQBIA
C
C     CALCULATE NEW RELATIVE CONCENTRATIONS FOR EACH GRID.
C
      DO 570 J=2,NC1
      DO 570 I=2,NR1
      IF (CS(I,J) .GT. 2.0) GO TO 590
      IF (HP(I,J) .GT. G(I,J)) GO TO 580
      CT(I,J)=CO(I,J)+(CT(I,J)+SQR(I,J)*CSQR(I,J))*(43560./(DX(I,J)*DY(I
     1,J)*PHI(I,J)*(HP(I,J)-Z(I,J)) +Q(I,J) * DT + SQR(I,J)))
      GO TO 570
  580 CT(I,J)=CO(I,J)+(CT(I,J)+SQR(I,J)*CSQR(I,J))*(43560./(DX(I,J)*DY(I
     1,J)*(PHI(I,J)*(G(I,J)-Z(I,J))+PHIC(I,J)*(HP(I,J)-G(I,J))) -QPUM(I,
     2J)+SQR(I,J)))
      GO TO 570
  590 CT(I,J)=CS(I,J)-2.
  570 CONTINUE
      TIME=ITIME*DT
      WRITE(6,430) TIME
      CALL MATROP (NR,NC,CT)
      DO 397 J=1,NC
      DO 397 I=1,NR
      CO(I,J)=CT(I,J)
  397 CONTINUE
      RETURN
C
  400 FORMAT (1H1,29X, 56HDISCHARGE IN I-DIRECTION (AC-FT/DT) FOR INCREM
     1ENT NUMBER,I6)
  410 FORMAT (1H1,29X, 56HDISCHARGE IN J-DIRECTION (AC-FT/DT) FOR INCREM
     1ENT NUMBER,I6)
  420 FORMAT (1H1,22X, 74HRIVER FLOW IN EACH GRID MINUS MEANS FLOW FROM
     1AQUIFER             (AC-FT/DT),/,1H ,49X, 16HINCREMENT NUMBER,I6)
C
  430 FORMAT (1H1,30X, 27HRELATIVE CONCENTRATION (CA),G10.2,4HDAYS)
      END
```

# SUBROUTINE BALCOP

```
      SUBROUTINE BALCOP (J1,J2,I,STTTEM,STATEM)
C
C
C     THIS SUBROUTINE WRITES OUT THE BALANCE COMPUTATIONS FOR EACH
C       TIME INCREMENT.  ALL UNITS ARE IN AC-FT PER TIME INCREMENT.
C
C       SQA,SQT - APPLIED WATER, BETWEEN STATIONS, TOTAL AREA.
C       SQRA,SQRT - INFLOW FROM RIVER, BETWEEN STATIONS, TOTAL AREA.
C       SQBA,SQBT - BOUNDARY INFLOW, BETWEEN STATIONS, TOTAL AREA.
C       STT,STTTEM - TOTAL AREA STORAGE AND DECREASE OF STORAGE.
C       STA,STATEM - BETWEEN STATIONS STORAGE AND DECREASE OF STORAGE.
C       STOL - STORAGE OF OVERLAP AREAS.
C       OVA,OVT - ILLEGALLY WITHDRAWN.
C       ASTA,ASTT - TOTALS. BETWEEN STATIONS, TOTAL AREA.
C
      COMMON /BLK2/ STA,STOL,STT,SQA,SQT,SQRA,SQBA,SQRT,SQBT,OVA,OVT
C
      WRITE (6,110) J1,J2,I
      WRITE (6,120) SQA,SQT
      WRITE (6,130) SQRA,SQRT
      WRITE (6,140) SQBA,SQBT
      STTTEM=STTTEM-STT
      STATEM=STATEM-STA
      WRITE (6,150) STT,STTTEM
      WRITE (6,160) STA,STATEM
      WRITE (6,170) STOL
      WRITE (6,180) OVA,OVT
      ASTA=SQA+SQRA+SQBA+STATEM+OVA
      ASTT=SQT+SQRT+SQBT+STTTEM+OVT
      WRITE (6,190) ASTA,ASTT
      RETURN
C
```

```
  110 FORMAT (1H1,13X, 55HMASS BALANCE COMPUTATIONS (AC-FT/DT) FOR SIMUL
     1ATED TIME,I9,  1H-,I9, 26H    AS AT THE END OF PERIOD,I3,///)
  120 FORMAT (50H0     APPLIED WATER (BETWEEN STATIONS - TOTAL AREA),20X,
     12F15.2)
  130 FORMAT (54H0     INFLOW FROM RIVER (BETWEEN STATIONS - TOTAL AREA),
     116X,2F15.2)
  140 FORMAT (52H0     BOUNDARY INFLOW (BETWEEN STATIONS - TOTAL AREA),18
     1X,2F15.2)
  150 FORMAT (47H0     TOTAL AREA STORAGE AND DECREASE OF STORAGE,8X,F15.
     12,15X,F15.2)
  160 FORMAT (53H0     BETWEEN STATIONS STORAGE AND DECREASE OF STORAGE,2
     1X,2F15.2)
  170 FORMAT (29H0     STORAGE OF OVERLAP AREAS,26X,F15.2/)
  180 FORMAT (56H0     ILLEGALLY WITHDRAWN (BETWEEN STATIONS - TOTAL AREA
     1),14X,2F15.2)
  190 FORMAT (49H-     T O T A L S  (BETWEEN STATIONS - TOTAL AREA),21X,2
     1F15.2)
C
      END
```

# SUBROUTINE MATROP

```
      SUBROUTINE MATROP (NOROW,NOCOL,B)
C
C
C     THIS SUBROUTINE ORGANIZES DATA OR RESULTS INTO A SUITABLE FORM
C       FOR PRINTING AND PRINTS.
C
      DIMENSION B(NOROW,NOCOL)
C
      NOCOLM=NOCOL
      ICONT=1
      NO1=NOCOLM
      IF (NOCOLM.GT.12) NO1=12
  110 NO2=NOCOLM-12
      WRITE (6,140) (JJ,JJ=ICONT,NO1)
      DO 120 I=1,NOROW
  120 WRITE (6,150) I,(B(I,J),J=ICONT,NO1)
      IF (NO2.LE.0) RETURN
      NOCOLM=NOCOLM-12
      ICONT=ICONT+12
      IF (NOCOLM.LE.12) GO TO 130
      NO1=ICONT+11
      GO TO 110
  130 NO1=ICONT-1+NOCOLM
      GO TO 110
C
  140 FORMAT (1H ,//,3X,12(7X,  1HX,I2)/)
  150 FORMAT (1H ,  1HY,I2,12F10.3)
C
      END
```

# SUBROUTINE READC

```
      SUBROUTINE READC (NR,NC,CAPW,CRCHR,CSOR,CO,LBC,RBC,TBC,BBC,AGGIE)
C
C
C     THIS SUBROUTINE READS IN RELATIVE CONCENTRATIONS OF SOURCE WATERS
C     WHICH MAY CHANGE WITH EACH TIME INTERVAL.
C
C     CAPW=CONCENTRATION IN APPLIED WATER
C     CRCHR=CONCENTRATION IN ARTICICIALLY RECHARGED WATERS
C     CSOR=CONCENTRATION IN WATERS FROM CONSTANT HEAD GRIDS
C     CO=CONCENTRATION IN BOUNDARY GRIDS WHERE WATER FLOES INTO THE GRID
C        SYSTEM
C
```

```
      DIMENSION CAPW(NR,NC), CRCHR(NR,NC), CSQR(NR,NC),CO(NR,NC)
      IF (AGGIE .EQ. 0.0) GO TO 180
      IF (AGGIE .LT. 0.0) GO TO 230
C
      NR1=NR-1
      READ (5,500) CCAPW
      IF (CCAPW .LT. 0.0) GO TO 100
      DO 110 J=1,NC
      DO 110 I=1,NR
  110 CAPW(I,J)=CCAPW
      GO TO 120
  100 READ (5,510) CAPW
C
  120 READ (5,500) CCRCHR
      IF (CCRCHR .LT. 0.0) GO TO 130
      DO 140 J=1,NC
      DO 140 I=1,NR
  140 CRCHR(I,J)=CCRCHR
      GO TO 150
  130 READ (5,510) CRCHR
C
  150 READ (5,500) CCSQR
      IF (CCSQR .LT. 0.0) GO TO 160
      DO 170 J=1,NC
      DO 170 I=1,NR
  170 CSQR(I,J)=CCSQR
      GO TO 180
  160 READ (5,510) CSQR
C
  180 IF (LBC .NE. 10000.) GO TO 190
  280 IF (RBC .NE. 10000.) GO TO 200
  290 IF (TBC .NE. 10000.) GO TO 210
  300 IF (BBC .NE. 10000.) GO TO 220
      GO TO 230
  190 READ (5,510) (CO(I,1), I=2,NR1)
      GO TO 280
  200 READ (5,510) (CO(I,NC), I=2,NR1)
      GO TO 290
  210 READ (5,510) (CO(1,J), J=1,NC)
      GO TO 300
  220 READ (5,510) (CO(NR,J), J=1,NC)
  500 FORMAT (1F10.1)
  510 FORMAT (8F10.1)
  230 CONTINUE
      END
```

# APPENDIX E

# DATA CODING FORMAT

**IBM** FORTRAN Coding Form — GX28-7327-6 U/M 050** Printed in U.S.A.

PROGRAM: WTQUAL2 — PAGE 1 OF 6

PROGRAMMER: L.W. PITTMAN — DATE: DECEMBER '77

PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH — CARD ELECTRO NUMBER*

| | FORTRAN STATEMENT | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | TITLE | | | | | | | | |
| | 8A10 | | | | | | | | |
| 2 | NR | NC | NW | NP | ICFAQ | ILKAQ | DT | ST | FWTØP |
| | I5 | I5 | I5 | I5 | I5 | I5 | F10.1 | F10.1 | F10.1 |
| 2A | AGGIE | | | | | | | | |
| | F10.1 | | | | | | | | |
| 3 | DLX | DLY | FFK | ZZ | GG | PPHI | CCA | PPHIC | |
| | F10.1 | F10.1 | F10.1 | F10.1 | F10.1 | F10.1 | F10.1 | F10.1 | |
| 3A | DX | DX → (NC * F10.1) | | | | | | | |
| 3B | DY | DY → (NR * F10.1) | | | | | | | |
| 3C | FK | FK → (NR * NC) * (F10.1) | READ IN BY CØLUMNS | | | | | | |
| 3D | Z | Z → (NR * NC) * (F10.1) | READ IN BY CØLUMNS | | | | | | |
| 3E | G | G → (NR * NC) * (F10.1) | READ IN BY CØLUMNS | | | | | | |
| 3F | PHI | PHI → (NR * NC) * (F10.1) | READ IN BY CØLUMNS | | | | | | |

Cards 3A–3F: ØMIT IF SPECIFIED IN CARD 3

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

**IBM** FORTRAN Coding Form

GX28-7327-6 U/M 050** Printed in U.S.A.

| | | | |
|---|---|---|---|
| PROGRAM | WTQUAL2 | PUNCHING INSTRUCTIONS | GRAPHIC |
| PROGRAMMER | L.W. PITTMAN | DATE DECEMBER '77 | PUNCH |
| PAGE 2 OF 6 | CARD ELECTRO NUMBER* | | |

| Card | Statement Number | FORTRAN Statement | |
|---|---|---|---|
| 3G | CA | CA $\nrightarrow$ (NR * NC) * (F10.1) READ IN BY CØLUMNS | ØMIT IF SPECIFIED IN CARD 3 |
| 3H | PHIC | PHIC $\nrightarrow$ (NR * NC) * (F10.1) READ IN BY CØLUMNS | |
| 33 | CSS F10.1 | {UNIFØRM VALUE ØF INITIAL AQUIFER CØNCENTRATIØN, ØTHERWISE BLANK CARD} | |
| 33A | CS | CS $\nrightarrow$ (NR * NC) * (F10.1) READ IN BY CØLUMNS<br>USE CØDED VALUES | ØMIT IF SPECIFIED IN CARD 33 |
| 34 | CCPPT F10.1 | {UNIFØRM VALUE ØF INITIAL PRECIPITATIØN CØNCENTRATIØN, ØTHERWISE BLANK CARD} | |
| 34A | CPPT | CPPT $\nrightarrow$ (NR * NC) * (F10.1) READ IN BY CØLUMNS | ØMIT IF SPECIFIED IN CARD 34 |
| 35 | CCAPW F10.1 | {UNIFØRM VALUE ØF INITIAL CØNCENTRATIØN IN WATER APPLIED AS IRRIGATIØN, ØTHERWISE BLANK CARD} | |
| 35A | CAPW | CAPW $\nrightarrow$ (NR * NC) * (F10.1) READ IN BY CØLUMNS | ØMIT IF SPECIFIED IN CARD 35 |
| 36 | CCRCHR F10.1 | {UNIFØRM VALUE ØF INITIAL CØNCENTRATIØN IN WATER RECHARGED THRU PITS AND LINE SØURCES, ØTHERWISE BLANK CARD} | |

*A standard card form, IBM electro 888157, is available for punching statements from this form

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IBM **FORTRAN Coding Form** GX28-7327-6 U/M 050** Printed in U.S.A.

PROGRAM: WTQUAL2 | PROGRAMMER: L.W. PITTMAN | DATE: DECEMBER '77 | PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH | PAGE 3 OF 6 | CARD ELECTRO NUMBER*

| Card | FORTRAN Statement | | | | | Remarks |
|---|---|---|---|---|---|---|
| 36A | CRCHR | CRCHR → (NR * NC) * (F10.1) | | | READ IN BY COLUMNS | OMIT IF SPECIFIED IN CARD 36 |
| 37 | CCSQR<br>F10.1 | UNIFORM VALUE OF INITIAL CONCENTRATION IN WATERS ORIGINATING FROM CONSTANT HEAD SOURCES, OTHERWISE BLANK CARD | | | | |
| 37A | CSQR | CSQR → (NR * NC) * (F10.1) | | | READ IN BY COLUMNS | OMIT IF SPECIFIED IN CARD 37 |
| 4 | HW<br>F10.1 | LBC<br>F10.1 | RBC<br>F10.1 | TBC<br>F10.1 | BBC<br>F10.1 | |
| 4A | H | H → (NR * NC) * (F10.1)<br>USE CODED VALUES | | | READ IN BY COLUMNS | OMIT IF SPECIFIED IN CARD 4 |
| 44 | HHL<br>F10.1 | TTL<br>F10.1 | FFKL<br>F10.1 | OMIT UNLESS LEAKY AQUIFER CONDITIONS ARE DESIRED | | |
| 44A | HL | HL → (NR * NC) * (F10.1) | | | READ IN BY COLUMNS | OMIT IF SPECIFIED IN CARD 44 |
| 44B | TL | TL → (NR * NC) * (F10.1) | | | READ IN BY COLUMNS | |
| 44C | FKL | FKL → (NR * NC) * (F10.1) | | | READ IN BY COLUMNS | |

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**IBM** FORTRAN Coding Form

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| | | | |
|---|---|---|---|
| PROGRAM | WTQUAL2 | PUNCHING INSTRUCTIONS | GRAPHIC / PUNCH |
| PROGRAMMER | L.W. PITTMAN | DATE | DECEMBER '77 |
| PAGE | 4 OF 6 | CARD ELECTRO NUMBER* | |

| STATEMENT NUMBER | FORTRAN STATEMENT |
|---|---|
| 5 | PPT F10.1   CPT F10.1   } IF NØNE, BLANK CARD |
| 5A | YPT YPT YPT YPT $\not\rightarrow$ INYR * (F5.1) } ØMIT IF PPT .LE. 0.0 |
| 6 | APW F10.1   CAW F10.1   } IF NØNE, BLANK CARD |
| 6A | YAW YAW YAW YAW $\not\rightarrow$ INYR * (F5.1) } ØMIT IF APW .LE. 0.0 |
| 7 | NGPU IS } ZERØ IF NØNE; BLANK INDICATES ENTIRE PHR MATRIX TO BE READ IN |
| 7A | J IS   K IS ↓ NGPU   PHR F10.1 } FØR NGPU .GT. 0.0, ØTHERWISE ØMIT |
| 7AA | PHR F10.1   PHR F10.1 $\not\rightarrow$ (NR * NC) * (F10.1) READ IN BY CØLUMNS FØR NGPU = BLANK |
| 7B | YPR YPR YPR YPR $\not\rightarrow$ INYR * (F5.1) } ØNLY NEEDED IF PHR .GT. 0.0 |

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**IBM** FORTRAN Coding Form

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| | | | |
|---|---|---|---|
| PROGRAM | WTQUAL2 | PUNCHING INSTRUCTIONS | PAGE 5 OF 6 |
| PROGRAMMER | L.W. PITTMAN | DATE DECEMBER '77 | |

| Card | Statement Number | Cols 7–10 | Cols 11–14 | FORTRAN Statement | Remarks |
|---|---|---|---|---|---|
| 77 | NW | | | | |
| | IS | | | | |
| 77A | IWNO | K | L | RPUM CAM | |
| | IS | IS | IS | F10.1 F10.1 | |
| 77B | YPM | YPM ↓ NW | YPM | → INYR * (F5.1) | IF BLANK ASSUMES SAME DISTRIBUTION AS PREVIOUS WELL; NØT NEEDED IF NW = 0 IN CØNTRØL CARD |
| 777 | NP | | | IF MAXIMUM NUMBER ØF WELLS IS GREATER THAN ZERØ, ØTHERWISE ØMIT | |
| | IS | | | | |
| 777A | INPØ | K | L | RCHR | |
| | IS | IS | IS | F10.1 | |
| 777B | YRC | YRC ↓ NP | YRC | → INYR * (F5.1) | IF BLANK ASSUMES SAME DISTRIBUTIØN AS PREVIØUS PIT; NØT NEEDED IF NP = 0 IN CØNTRØL CARD |
| 7777 | REPEAT | | | IF BLANK, REPEAT CARDS 5 THRØUGH 777B FØR NEXT YEAR ØF ANALYSIS | |

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IBM

FORTRAN Coding Form

GX28-7327-6 U/M 050**
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PROGRAM: WTQUAL 2

PROGRAMMER: L.W. PITTMAN

DATE: DECEMBER '77

PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH

PAGE 6 OF 6

CARD ELECTRO NUMBER*

| STATEMENT NUMBER | | FORTRAN STATEMENT | | | IDENTIFICATION SEQUENCE |
|---|---|---|---|---|---|
| 8 | CCAPW<br>F10.1 | } UNIFØRM VALUE ØF NEW CØNCENTRATIØN ØF WATER<br>APPLIED AS IRRIGATIØN, ØTHERWICE BLANK CARD | | | |
| 8A | CAPW | CAPW —/→ (NR * NC) * (F10.1) | READ IN BY CØLUMNS | | |
| 9 | CCRCHR<br>F10.1 | } UNIFØRM VALUE ØF NEW CØNCENTRATIØN ØF WATER RECHARGED<br>THRU PITS AND LINE SØURCES, ØTHERWISE BLANK CARD | | NØT NEEDED IF<br>AGGIE .LE. 0.0 | |
| 9A | CRCHR | CRCHR —/→ (NR * NC) * (F10.1) | READ IN BY CØLUMNS | IF USED, MUST BE READ<br>IN FØR EACH DT | |
| 10 | CCSQR<br>F10.1 | } UNIFØRM VALUE ØF NEW CØNCENTRATIØN ØF WATERS ØRIGINATING<br>FRØM CØNSTANT HEAD SØURCES, ØTHERWISE BLANK CARD | | | |
| 10A | CSQR | CSQR —/→ (NR * NC) * (F10.1) | READ IN BY CØLUMNS | | |
| 11 | CØ | FØR LEFT BOUNDARY —/→ (NR-2) * (F10.1) | | ØNLY NEEDED IF AGGIE .LT. 0.0 | |
| 12 | CØ | FØR RIGHT BØUNDARY —/→ (NR-2) * (F10.1) | | | |
| 13 | CØ | FØR TØP BØUNDARY —/→ NC * (F10.1) | | | |
| 14 | CØ | FØR BØTTØM BØUNDAY —/→ NC * (F10.1) | | | |

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