AQUIFEM-SALT

A FINITE-ELEMENT MODEL FOR AQUIFERS CONTAINING A SEAWATER INTERFACE

By Clifford I. Voss

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 84—4263

1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

Chief Hydrologist
U.S. Geological Survey
430 National Center
Reston, Virginia 22092

Copies of this report can be
purchased from:

U.S. Geological Survey
Open-File Services Section
Western Distribution Branch
Box 25425, Federal Center
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

AQUIFEM-SALT

A FINITE ELEMENT MODEL FOR AQUIFERS CONTAINING A SEAWATER INTERFACE

By Clifford I. Voss

ABSTRACT

This report describes modifications to AQUIFEM (Pinder, Frind, Trescott and Voss, 1979), a finite element areal ground-water flow model for aquifer evaluation. The modified model, AQUIFEM-SALT, simulates an aquifer containing a freshwater body that freely floats on seawater. Parts of the freshwater lens may be confined above and below by less permeable units. Theory, code modifications, and model verification are discussed. A modified input data list is included. This report is intended as a companion to the original AQUIFEM documentation (Pinder and Voss, 1979).

INTRODUCTION

Analysis of an aquifer system containing both fresh water and salt water may be carried out based on a number of different conceptual models. The proper choice of a conceptual model and method of analysis is best determined by the aquifer system's physical controls on the behavior of interest in the study. A complete range of numerical modeling tools are available. These include cross-sectional or three-dimensional fluid-density-dependent flow- and solute-transport simulation (e.g. Segol, et al(1975), Voss(1984)) allowing a dispersed interface between fresh water and salt water. Also available are sharp interface methods in cross-sectional simulation (e.g. Volker and Rushton(1982)) or areal aquifer simulation (e.g. Pinder and Page(1976), Sa da Costa and Wilson(1979), Mercer, et al(1980)) which account for movement of both fresh water and salt water. In addition, analytical and semi-analytical methods are available for some sharp and dispersed interface problems (e.g. Bear(1979), Todd(1980)).

What is described here is an areal groundwater model, AQUIFEM-SALT which falls in the sharp interface class of methods. This model simulates head changes in and movement of only the fresh water in an aquifer system which may contain both fresh and salt water. Basically, this model is a standard areal transient ground-water flow simulator for confined or unconfined aquifers with the following generalization: the bottom of the freshwater aquifer may be either a lower confining unit or the interface between fresh water and salt water. The interface position is determined by hydrostatic equilibrium between fresh and salt water and the position and intersection of the interface with a lower or upper confining unit may change with time due to changing freshwater heads.

Although a three-dimensional-density-dependent transport model may theoretically be used to simulate any entire saltwater-freshwater aquifer system, such an exercise is most often neither practical nor worthwhile. Transport model simulation is called for only when the dispersed nature of the fresh to salt water transition zone and actual salt concentration distributons are of key interest. In cases where actual salt concentrations are not of central importance but rather bulk fresh and salt water movements are, use of a sharp interface model is likely the most practical approach. Moreover, when the aquifer system must be studied in the areal sense, two kinds of numerical models are available. A two-fluid simulator couples an areal ground water flow model for fresh water with an areal ground water flow model for salt water allowing transient simulation of horizontal fresh and saltwater movement (Pinder and Page(1976), Mercer, et al(1980), Sa da Costa and Wilson(1979)). A one-fluid fresh water simulator presented here, AQUIFEM-SALT, is essentially a transient areal ground water flow simulator for the fresh water which assumes hydrostatic equilibrium in the salt water.

The two-fluid approach is somewhat more general as it allows for a time lag in movements of the freshwater-saltwater interface caused by fluid stresses on the ground water system. This model for the time lag is due to the finite amount of time it takes for the salt water to flow horizontally to or from the interface as the interface attempts to readjust to a hydrostatic equilibrium elevation. The one-fluid approach assumes that the interface adjusts very quickly to an equilibrium position as compared to the time frame of stresses of interest and ignores any lag due to transient horizontal saltwater flow. Both one and two-fluid models ignore lags due to other physical processes.

Both types of models are areal and by definition ignore any vertical inhomogeneities in the aquifer. Also, they ignore the commonly found horizontal to vertical anisotropy of hydraulic conductivity in stratified aquifers. Further, they ignore vertical flows due to recharge and partially penetrating wells. Any of these ignored effects may, in fact, comprise significant controls on the elevation and transient vertical movement of the interface especially in the time immediately following changes in fluid stress on the aquifer system. Neither the one-fluid freshwater model, nor the two-fluid model which accounts for vertically averaged horizontal flow of salt water may be employed to analyze aquifer hydraulics controlled by these features. For example, a large part of an observed time lag for the interface position in an anisotropic aquifer to readjust is due to the low vertical conductivity. Not even the two-fluid model, which allows time lags resulting from horizontal salt water flow, can account for this lag which is due mainly to resistance to vertical flow of fresh and salt water.

AQUIFEM-SALT and other single fluid models may, in fact, be the most practical and effective models for areal analysis of many complex freshwater-saltwater aquifer systems. AQUIFEM-SALT is based on a clear set of assumptions which allow the freshwater-saltwater system to be treated in analysis as a "standard" areal freshwater aquifer which is simulated using a "standard" ground water model. The additional generality provided by the two-fluid models is not always advantageous in representing field data as, commonly, important complexities involving vertical flow, inhomogeneity, and anisotropy exist which no areal analysis can represent. Moreover, given that in many cases there is a lack of areal data on the salt water portions of the aquifer, the value of introducing the additional complexity of modeling salt water dynamics with the two-fluid model is questionable as it can never be verified.

Shortcomings in areal modeling must be recognized when carrying out such analyses. When an areal analysis is required, a one-fluid model such as AQUIFEM-SALT, is often the type which should be used as it is based on the simplest set of assumptions and does not tend to over-model or over-represent the hydrologic system.

When using AQUIFEM-SALT to analyze a complex field problem, systematic errors in matching either spatial distributions of freshwater heads or temporal changes in heads should be interpreted on the basis of which aquifer features or processes are not represented by the areal approach. This may lead to some ambiguity in calibrated hydraulic conductivity and storage values but at least the presence of ambiguity may be recognized and its source understood.

THEORY

The mathematical model upon which AQUIFEM (Pinder and Voss, 1979) is based follows:

$$s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} (\lambda \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (\lambda \frac{\partial h}{\partial y}) + Q + Q_L \qquad (1)$$

where:

h = $h(x,y,t)$ is the hydraulic head in the freshwater body [L]

s = $s(x,y)$ is a storage coefficient defined below [L^o]

λ = is { transmissivity $T(x,y)$ for portions of the aquifer confined both above and below [L^2T^{-1}]; product of hydraulic conductivity and aquifer thickness, $\lambda(x,y,t) = Kb$, for aquifer portions unconfined either above or below }

K = $K(x,y)$ is the hydraulic conductivity of the aquifer [LT^{-1}]

b = $b(x,y,t)$ is the saturated freshwater thickness of the aquifer, defined below [L]

Q = $Q(x,y)$ is the strength of a source function, that is: volume of freshwater per time added per horizontal area of the aquifer $(L^3/T)/(L^2$ aquifer) [$L\ T^{-1}$]

Q_L = $Q_L\ (x,y,t)$ is the strength of leakage into the freshwater body that is: volume of freshwater leakage into the aquifer per time and in per horizontal area of aquifer $(L^3/T)/(L^2$ aquifer) [$L\ T^{-1}$]

This equation describes the conservation of freshwater fluid mass in an aquifer. In a free floating lens of freshwater upon seawater where freshwater density is 1000 kg/m^3 and saltwater density is 1025. kg/m^3 under certain conditions, the lens may be assumed to have a thickness at any point of 41 times the local freshwater head. A freshwater lens conceptualized in this manner is known as Ghyben-Herzberg lens (see, for example, Bear (1979) Chapter 9, or Todd(1980) Chapter 14). This model of the freshwater-saltwater system presupposes hydrostatic equilibrium between columns of fresh and salt water.

The utility of this Ghyben-Herzberg equilibrium lens model for analysis of a particular aquifer system depends on how well the phenomena being studied fit the inherent assumptions of 1) a sharp interface, 2) vertical hydrostatic equilibrium in both fresh and salt water (no vertical flows), and 3) constant head in the salt water. Often, the equilibrium lens model is a useful representation of the lens for study of some aspects of lens behavior, and totally inappropriate for analysis of other behaviors. For example, meaningful and thus useful long term regional water balance studies of an aquifer are usually well founded using the equilibrium lens model. However, use of the same model to study the flow beneath a partially penetrating well in the same aquifer is clearly not warranted. Thus, as with any analytical or modeling method, the applicability of the analysis must be carefully considered in light of the phenomena being studied. In evaluating the applicability of the AQUIFEM-SALT equilibrium lens model to study particular aquifer behavior, the following criteria should be considered and discussed in any report of modeling results :

1. Sharp interface. Criterion: 'The freshwater and saltwater bodies do not mix and the interface is sharp.' This criterion need not be absolutely true, for example, the transition from 20 percent to 80 percent seawater may occur over less than 10 percent of lens thickness for the lens to be considered relatively sharp. Often the transition is not sharp near discharge areas and in areas of strong pumping. In such areas, the utility of this model is limited to regional water balance interpretations, as it is not clear that the simulated sharp interface elevation represents the 50% isochlor or any other particular concentration level.

2. Vertical hydrostatic equilibrium. Criterion: 'Both the fresh water and salt water are in vertical hydrostatic equilibrium, and vertical flows are either non-existent in the aquifer, or unimportant to the phenomena being studied.' Thus, as with any areal model, all wells are assumed to fully penetrate the freshwater lens, and the same average horizontal flow is assumed to occur throughout the depth of the freshwater lens at any areal point.

Surface recharge or discharge or a partially penetrating well will concentrate stress at a particular depth in the lens and locally cause a non-hydrostatic condition with vertical flow. Vertical to horizontal anisotropy of hydraulic conductivity tends to exaggerate such partial penetration effects, and causes even greater disequilibrium. The vertical disequilibrium is strongest near the partially penetrating stress. However, no areal model can account for these effects, and lens phenomena which are based largely on vertical flow may not be analyzed with AQUIFEM-SALT. Some lens phenomena may be somewhat affected, but not entirely controlled by vertical disequilibrium and may be studied with AQUIFEM-SALT if results are carefully interpreted.

3. <u>Constant saltwater head</u>. Criterion: 'The head in the saltwater portion of the aquifer is constant in both time and space.' Further, the saltwater head is used as the zero datum for all other measures of head or interface levels. Saltwater head would remain constant only in the ideal aquifer where hydraulic conductivity in the saltwater portion is infinitely great. In this ideal aquifer, an infinitesimally small gradient in saltwater head would drive as much flow as necessary to supply salt water beneath the moving interface. A change in freshwater head, Δh, would instantly result in a vertical move of the interface of $40\Delta h$. Clearly, in real aquifers, the movement of salt water is impeded by the finite conductivity of the saltwater portion and some delay occurs in supplying salt water below a moving interface. Thus, after a change in head, Δh, the change in the equilibrium interface position of $40\Delta h$ would be reached only after a delay. In analogy with a phreatic aquifer, which has a delayed yield due to the presence and movement of the water table, the lens apparently exhibits another kind of delayed yield due to the presence and movement of the interface. Moreover, the period of delay in lens storage may be significant. After a stress in a real aquifer, the saltwater head at the interface achieves its constant value only after enough salt water moves about to equalize saltwater heads. On the other hand, at the water table, head is constant at all times. Thus, one would expect longer periods of delayed yield at the saltwater interface than at the water table.

This consideration implies a restriction on the applicability of the equilibrium lens model and AQUIFEM-SALT for analysis of 'short term' lens behavior. No absolute criterion measure of 'short term' is available because a relative length of time is measured by comparing the time scale of the particular lens behavior of interest with the response time of the interface. 'Short term' behavior takes place in a time frame on the order of lens relaxation time. For example, should it take one year for the interface to come to equilibrium after a stress, then simulating lens response to a pumping rate which changes monthly is meaningless as the equilibrium lens model can respond only to, say, average yearly pumping rates.

Note that decreasing values of specific yield during model calibration by ten to forty times over actual values would, in fact, cause the model to respond quickly to 'short term' stresses. Thus, a match could be obtained with 'short term' fluctuations in head by artificially removing the large yield due to movement of the interface. The result is that while 'short term' responses can be simulated with the equilibrium model, the calibrated specific yields may be ambiguous and depend on the time scale of stresses used during the calibration rather than on aquifer properties.

Partial penetration and horizontal anisotropy in hydraulic conductivity exacerbate this problem. For example, a partially penetrating well near the water table in an anisotropic aquifer with low vertical hydraulic conductivity would stress the water table significantly more than the saltwater interface. 'Short term' stresses at this well would affect the aquifer mainly through water-table aquifer hydraulics, and not through movement of the interface. When partial penetration or vertical effects are significant, no equilibrium type or other areal model properly represents the aquifer behavior. Only two-dimensional cross-sectional models or three-dimensional models which can account for the vertical geometry of well, water table, and interface with density differences are appropriate. However, in such a case, the equilibrium lens model is still appropriate for regional 'long term' analysis.

For the present set of modifications, the aquifer is assumed to consist of parts that may be either of two types, (1) a 'confined' type in which the freshwater body has a fixed known thickness and where it is always confined above and below, and (2) a 'free' type in which the freshwater may be unconfined or confined on either top or bottom.

The 'free' aquifer type may represent any of the four situations shown in Figure 1 and one type may change to another in time, depending on changes in head. The confined aquifer type, however, represents only the confined above and below situation and may never become unconfined. The 'free' type requires data for aquifer top and bottom elevations, storage coefficient, specific storage and hydraulic conductivity. The 'confined' type requires only storage coefficient and transmissivity. Note that the zero datum from which heads are measured is assumed to be at sea level, or at the hydrostatic level of the source body of salt water.

A total freshwater lens thickness is defined by allowing the aquifer bottom to be at the seawater interface at a depth 40h, unless the lens is truncated at a shallower depth by a confining layer, and by allowing the aquifer top to be the water table at elevation, h, unless the lens is truncated above by a confining layer. Thus, the variable, b, of equation (1) may be generalized as:

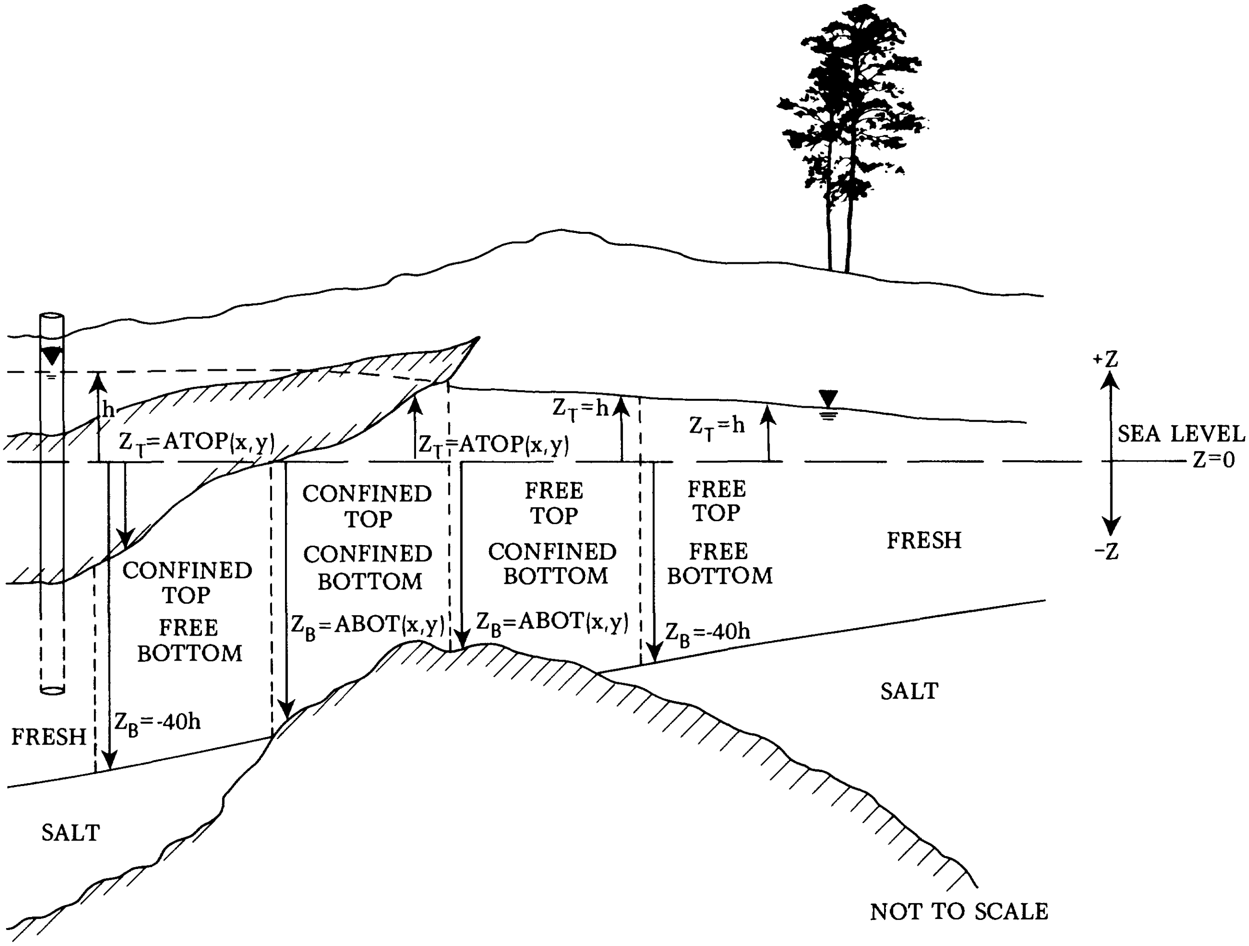


Figure 1. Conceptual cross-section of aquifer.
(Fresh-water lens thickness = $z_T - z_B$)

$$b = TOP - BOTTOM \qquad (2)$$

where

$$\text{TOP} \quad TOP(x,y,t) = \begin{cases} ATOP(x,y) & \text{when } h \geq ATOP(x,y) \\ h(x,y,t) & \text{when } h < ATOP(x,y) \end{cases} \quad [L]$$

$$\text{BOTTOM} \quad BOTTOM(x,y,t) = \begin{cases} ABOT(x,y) & \text{when } -40h \leq ABOT(x,y) \\ -40h(x,y,t) & \text{when } -40h > ABOT(x,y,t) \end{cases} \quad [L]$$

The total storativity may be defined for a freshwater lens which is unconfined on top and bottom by noting that a unit drop in head, Δh, releases water via three mechanisms. Water is released due to elastic storage in the entire thickness of the lens in quantity, $S_o \Delta h$, where S_o is the elastic storage coefficient. Also, water is released at the water table due to drainage in quantity, $\varepsilon \Delta h$, where ε is the specific yield or porosity, assuming these quantities to be equal. These two mechanisms are included in the equation for a phreatic aquifer rigorously derived by vertical integration of the groundwater mass balance, given as equation (5-79) in Bear(1979) on page 114. Additionally in the lens case, water is released by movement of the seawater interface in quantity $40\varepsilon\Delta h$, if the sea water below the interface remains in hydrostatic equilibrium with the changing freshwater head. Thus, a total storativity for a freshwater lens is given by the sum, $(S_o + 41\varepsilon)$. Note that this quantity is about 41 times greater than the storativity, ε, of a watertable aquifer with fixed bottom. This total storativity does not account for delayed yield at either water table or seawater interface.

The total storativity, s, of equation (1) may be defined in general for the lens case where either the top or bottom of the lens may be confined as:

$$s = s(x,y) = S_o + S_{TOP} + S_{BOT} \tag{3}$$

where

S_o		is the storage coefficient for water in elastic storage	$[L^o]$
$S_{TOP} = \begin{cases} 0 & \text{when } h \geq ATOP(x,y) \\ \varepsilon & \text{when } h < ATOP(x,y) \end{cases}$			$[L^o]$
$S_{BOT} = \begin{cases} 0 & \text{when } -40h \leq ABOT(x,y) \\ 40\varepsilon & \text{when } -40h > ABOT(x,y) \end{cases}$			$[L^o]$
ε	$\varepsilon(x,y)$	is the drainable porosity or specific yield of the aquifer	$[L^o]$
ATOP	ATOP(x,y)	is the elevation of the base of an upper confining layer (aquifer top)	[L]
ABOT	ABOT(x,y)	is the elevation of the top of a confining layer below the aquifer (aquifer bottom)	[L]

CODE MODIFICATIONS

When designing a mesh for simulation of an aquifer containing a seawater interface, a particular finite element is chosen to be either the 'confined' or 'free' type. Vertical leakage of fresh water through semi-confining layers may occur from both 'confined' and 'free' elements. The leakage may be considered to be through either an upper or lower confining layer. The fresh water leakage is assumed by the model to continue even when the water table drops below an upper confining layer and when the freshwater-saltwater interface rises above a lower confining layer.

In the computer code, for each 'confined' element, only the transmissivity and storage coefficient are employed in the calculations. The transmissivity is assigned a constant value over each 'confined' element.

A 'free' element undergoes a series of checks on each time step to see whether the aquifer top and bottom are currently confined or unconfined. Based on the results of these checks, the lens thickness is set according to (2) and the total lens storativity is set according to (3). The storativity given by (3) is assumed constant over each element and is based on the confining conditions and head at the center of each element. The 'free' element transmissivity is based on the product of thickness values at each node from (2) and hydraulic conductivity values specified in the input data, which may vary linearly from node to node. This results in 'free' element transmissivities that vary linearly between the nodes.

The confining conditions to be used for a new time step are based on projected rather than actual current heads. Projected head is the estimated value that head will take at a point in the current time step based on a linear extrapolation of the past two head values. The particular point in the present time step is given by the product of the time integration control (THETA) and the time step length.

An additional set of modifications convert the optional ground water mass balance calculation to the freshwater lens case. For 'free' elements the same parameters are adjusted as discussed above. The optional velocity calculation is unchanged for the lens case. Note that to properly employ these modifications, AQUIFEM-SALT must be used in <u>the water-table aquifer mode.</u> A description of simulation setup is given in the original documentation on pages 32 to 39, and in particular, on page 35 under "Parameter Specification for Water Table Problem."

MODEL VERIFICATION

The modified code was tested on two steady-state free lens solutions and one simple transient analytical solution. For a one-dimensional steady state solution, the governing equation may be written:

$$\frac{d}{dx}\left(\frac{41}{2} K \frac{dh^2}{dx}\right) + Q + Q_L = 0 \tag{4}$$

Case 1: Steady recharge only at upstream boundary

For the case where h(x = 0) = 0 (head at coast is at sea-level), no leakage (Q_L = 0) and q_{in} [ft^3/s] recharges the lens at the upstream boundary (at x = L), the analytical solution may be verified by substition into (4) to be:

$$h^2 = \frac{2q_{in}x}{41Kw} \tag{5}$$

where w is the width of the one-dimensional strip. In particular for the values q_{in} = 46.4 [ft^3/s], w = 1.5 miles, K = 0.0139 [ft/s], the solution is:

x [miles]	0.	1.	2.	3.	4.	5.	6.	10.
h [ft]	0.0	10.419	14.735	18.046	20.838	23.298	25.521	32.948

The strip was simulated with ten (1.0 mile x 1.5 mile) rectangular elements (22 nodes). In order to allow a completely unconfined lens on top and bottom for all elements, the 'free' element type was chosen for all elements and TOP and BOTTOM were set sufficiently high and low such that the lens would never intersect these boundaries. The numerical results agree with the analytical solution to five significant figures. The steady-state solution was iterative, requiring about twenty 'time steps' to converge to steady state from an initial head at all nodes of 1.0 ft, given that the specific yield is 0.1 and the time step is one year. Note that a number of time steps were employed to reach a steady state solution. A one-step steady solution is not possible as lens problems are non-linear.

Case 2: Steady recharge distributed along strip.

For the case of an impermeable upstream boundary at x = L, coastal head at sea-level (h(x = 0) = 0), no leakage ($Q_L = 0$) and recharge Q [ft/s] distributed over the entire strip, the analytical solution may be verified by substitution into (4) to be:

$$h^2 = \frac{QL^2}{41K} (1 - (\frac{L-x}{L}^2)) \tag{6}$$

In particular, for the values $Q = 1.11 \times 10^{-7}$ [ft/s], and other parameters as in Case 1, the solution is:

x [miles]	0.	1.	2.	10.
h [ft]	0.0000	10.157	13.981	23.302

After twenty iterations, as in Case 1, the steady-state numerical solution was obtained to five place agreement with the same mesh as in Case 1.

Rate of convergence to a steady-state solution may be increased by treating the ratio of specific yield to time step, ($\varepsilon/\Delta t$) as an iteration parameter. Lowering the ratio has the effect of increasing the rate of convergence. A value too low causes oscillation in head from time step to time step and may result in non-convergence. A ratio too high guarantees convergence but causes slow changes in heads between time steps. The optimal ratio is between these extremes and may only be found by numerical experiment.

Case 3: <u>Simple transient solution</u>

The modified code was tested for transient simulation by setting K = 0 at all nodes with all elements specified as 'free' without leakage, leaving only the following governing equation to be solved:

$$41\varepsilon \frac{dh}{dt} = Q \qquad (7)$$

This simple test may be viewed physically as a closed tank aquifer with recharge, Q. The solution may be verified by substitution into (7) to be:

$$h = \frac{Qt}{41\varepsilon} + h(t = 0) \qquad (8)$$

where h(t = 0) is the initial head. This predicts a linear increase in head with time. Numerical results for Case 3 were obtained using Case 2 parameters and THETA = 1.0.The numerical solution matched the analytical solution to five decimal places.

Thus, all terms of the modified governing equations were tested. This verifies the reliability of the changes to the code.

REFERENCES

Bear, J., 1979, Hydraulics of Groundwater, McGraw-Hill, New York.

Mercer, J. W., Larson, S. P. and Faust, C. R., 1980, Finite-difference Model to Simulate Areal Flow of Saltwater and Freshwater Separated by an Interface, U. S. Geological Survey Open File Report 80-407.

Pinder, G. F. and Page, R. H., 1977, Finite Element Simulation of Salt Water Intrusion on the South Fork of Long Island, in Finite Elements in Water Resources, W. G. Gray, G. F. Pinder, and C. A. Brebbia, eds., Pentech Press, London.

Pinder, G. F. and Voss, C., 1979, AQUIFEM, A Finite Element Model for Aquifer Evaluation (Documentation), Department of Water Resources Engineering, Royal Institute of Technology, Stockholm, Sweden, Report 7911; TRITA-VAT-3806. (Code prepared by G. Pinder, E. Frind, P. Trescott and C. Voss.)

Sa da Costa, A. A. G. and Wilson, J. L., 1979, A Numerical Model of Seawater Intrusion in Aquifers, M.I.T. Report 247, R. M. Parsons Laboratory for Water Resources and Hydrodynamics.

Segol, G., Pinder, G. F. and Gray, W. G., 1975, A Galerkin Finite Element Technique for Calculating the Transient Position of the Saltwater Front, Water Resources Research, 11, 343-347.

Todd, D. K., 1980, Groundwater Hydrology, John Wiley, New York.

Volker, R. E. and Rushton, K. R., 1982, An Assessment of the Importance of Some Parameters for Seawater Intrusion in Aquifers and a Comparison of Dispersive and Sharp Interface Modelling Approaches, Journal of Hydrology, 56, 239-250.

Voss, C. I., 1984, SUTRA: A Finite Element Simulation Model for Saturated-Unsaturated Fluid Density Dependent Groundwater Flow with Energy Transport or Chemically Reactive Single Species Solute Transport, U. S. Geological Survey Water Resources Investigations Report (in press).

Appendix : Input Data Formats for A Q U I F E M - S A L T

LIST OF INPUT DATA

Note: {} indicates an optional data set.

Variable	Format	
		Data Set 1: Identification of Data File
CARD	20A4	The program title, AQUIFEM, must be punched in columns 1-7. The remaining 73 positions may be used for labeling the data file, or may be left blank.
		Data Set 2: Output Title
TITLE	20A4	This card is reproduced as a heading on the program output.
		Data Set 3: Dimensioning Information
NN	I5	Total number of nodes in finite element mesh.
NE	I5	Total number of elements in the mesh.
NS	I5	Exact number of nodes where hydraulic head is specified as a known constant.
NB	I5	Estimated half-band width for global coefficient matrices. Should be equal to or not much greater than the exact half-band width, which is equal to the greatest difference between two node numbers in an element of all the elements in the mesh, plus one.
NF	I5	Exact number of nodes where fluid is injected or withdrawn.
NL	I5	Exact number of elements in the mesh in which vertical leakage may occur.

---------------------- Data Set 4: Temporal Operation Control----------------

TIME	F10.0	Maximum allowed aquifer simulation period in hours.
DELT	F10.0	Time step size (Δt) in hours.
CHNG	F10.0	Multiplier for automatic change in time step size The new time step size is obtained by multiplying the old time step size by CHNG.
ITMAX	I10	Maximum allowed number of time steps.
ITCHNG	I10	Number of time steps between automatic changes in time step size. If time step is to remain constant, ITCHNG must be set to a large number, e.g. 999999999.
THETA	F10.0	Time integration control ($0.5 \leq THETA \leq 1.0$). A value of 0.5 yields the Crank-Nicolson method (centered-in-time), 1.0 yields the implicit method. (backward difference in time). A value of 0.67 is recommended for combined stability and accuracy. Note that THETA is automatically set to 1.0 when a one-step steady-state simulation is undertaken (KOD5=1).

---------------------- Data Set 5: AQUIFEM Options--------------------------

-A value of 1 initiates an option.
-A value of 0 suppresses an option.
(Recommended values are specified below.)

KOD1	I4	Compute the ground-water fluid balance in the model aquifer after each time step.
KOD2 = 0	I4	Print out element coefficient matrices.
KOD3 = 0	I4	Print out global coefficient matrices.
KOD4 = 0	I4	Punch out the final hydraulic head values after simulation.

KOD5 = 0	I4	Compute steady-state solution in one step. (May not be used for watertable aquifers).
KOD6 = 0	I4	Print drawdown plot after each time step.
KOD7 = 1	I4	Print hydraulic head plot after each time step.
KOD8 = 0	I4	Print out known vector in matrix equation.
KOD9 = 1	I4	Read nodewise transmissivity (or for watertable problems, hydraulic conductivity) values.
KOD10 = 1	I4	Consider as watertable problem. Some (or all) elements are 'free' and thickness of freshwater lens changes with time. (if KOD10=1, then KOD9 must also be set to 1).
KOD11	I4	Compute velocity of ground water in the pores at all nodes after each time step.
KOD12	I4	Print velocity magnitude plot and velocity direction plot after each time step.
KOD13	I4	Printed output after each KOD13 time steps.

---------------------- Data Set 5A: Confined Aquifer Storage Coefficient

STOCOF	E15.7	Storage coefficient based on elastic storage for all 'free' elements in aquifer.

---------------------- Data Set 6: Node Coordinates ------------------------

Card (1)

FACTX	F10.0	Multipliers for automatic rescaling of X and Y node coordinates on the following cards. The
FACTY	F10.0	node coordinates employed in the model are automatically calculated by multiplication as, FACTX*X(J) and FACTY*Y(J). These factors may be used to convert English to SI units or to convert graph paper coordinates to field coordinates.

Cards (2 through NN+1)		(one card for each node in the mesh, NN cards)
J	I5	Node number.
X(J)	G10.0	X coordinate of the node.
Y(J)	G10.0	Y coordinate of the node.

--------------------- Data Set 7: Sources and Sinks (Injection and Withdrawal)-

IQ	I5	Node number where injection or pumping is specified.
FQ(IQ)	G10.0	Injection rate (+), Withdrawal rate (-) at the node in Volume/second.

If there are no source/sink nodes (NF=0) this data set is OMITTED. Otherwise there must be NF cards in this data set.

Known flows across model boundaries may also be specified in this data set as injections or withdrawals of fluid at nodes along the boundaries as indicated in Figure 2.

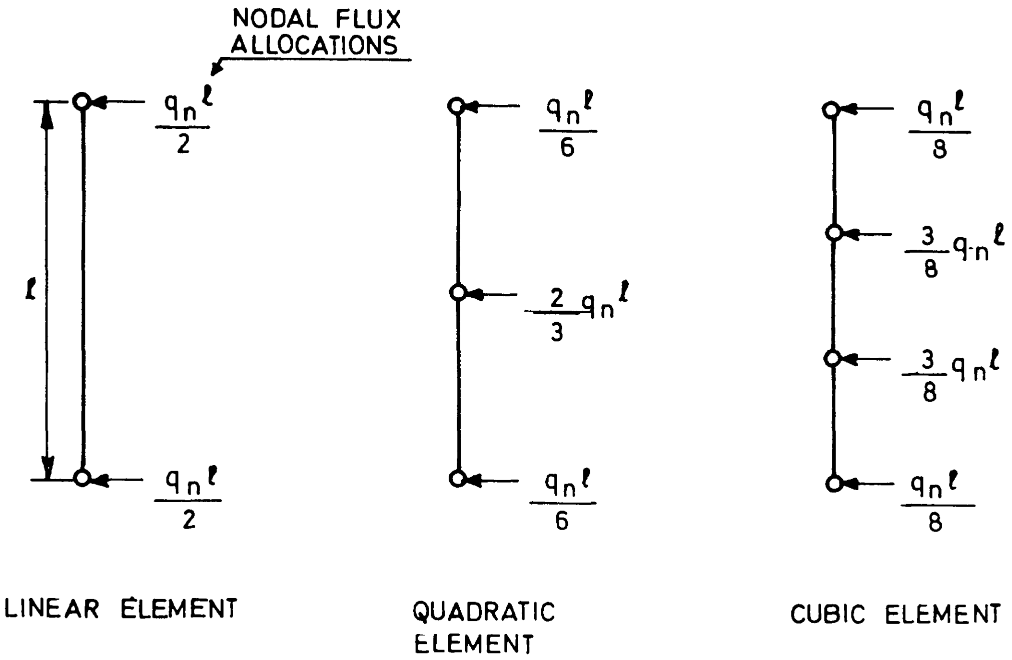


Figure 2. Allocation to boundary nodes of a constant normal flux q_n^{ℓ} acting along an element of side length ℓ.

--------------------		Data Set 8: Initial Hydraulic Head--------------------
UI	8F10.0	Values of hydraulic head in the aquifer at each of the nodes at the start of simulation. There are 8 values per card in order of node number; i.e.: first card refers to nodes 1-8, second card to nodes 9-16, third 17-24,... etc. The last card need not have 8 values.
--------------------		Data Set 9: Nodewise Hydraulic Conductivity-----------
PTRANS	8G10.0	Hydraulic conductivity values defined nodewise rather than elementwise. There must always be 8 values per card in order of node number as in DATA Set 8, and all nodes in the mesh must be given a value. Dummy values or blanks may, however, be assigned to nodes in the mesh where elementwise transmissivity (defined in Data Set 11) is used instead of nodewise hydraulic conductivity. Dummy or blank values are for nodes that appear exclusively in 'confined' elements. Nodes that appear in both 'free' and 'confined' elements must be assigned nodewise conductivity values.
-------------------		Data Set 10A: Aquifer Top Elevation---------------------
ATOP	8F10.0	Elevation of bottom of upper confining layer in the aquifer at all nodes. There must be 8 values per card in order of node number as in Data Set 8, and all nodes in the mesh must receive a value. Dummy values or blanks may, however, be assigned to nodes in the mesh which are associated exclusively with 'confined' aquifer elements. In order tha a node remain unconfined at the water table, ATOP must be set greater than the maximum expected head value, h, at the node.

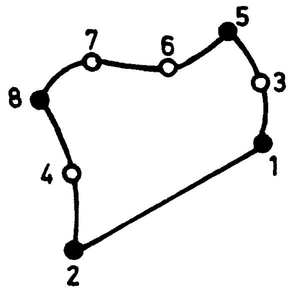
--------------------		Data Set 10B: Aquifer Bottom Elevation---------------------
ABOT	8F10.0	Elevation of top of lower confining layer in the aquifer at all nodes. There must be 8 values per card in order of node number as in Data Set 8, and all nodes in the mesh must receive a value. Dummy values or blanks may, however, be assigned to nodes in the mesh which are associated exclusively with 'confined' aquifer elements. In order that a node remain unconfined at the freshwater-seawater interface, ABOT must be set less than the minimum expected value of (-40h) at the node.
-------------------		Data Set 11: Elementwise Transmissivity, Storage & Recharge (one card for each element in the mesh, NE cards)
L	I5	Element number
TRANS(L)	G10.0	Transmissivity defined as a constant value over 'confined' aquifer element L. A positive value here indicates that this element is 'confined' having a fixed saturated thickness and thus a constant value of transmissivity for the entire simulation. Elements which are to be considered 'free' must be assigned a negative value for TRANS(L) in this data set. A 'free' element may change in the simulation between confined and unconfined conditions at both the water table and at the seawater interface depending on head changes.
STORAGE(L)	G10.0	Storage coefficient value defined as a constant over element L for 'confined' aquifer elements (where TRANS(L)>0). For 'free' elements (where TRANS(L)<0), STORAG(L) is defined as the value of drainable volumetric porosity (or specific yield) of the aquifer.

BLANKS	10X	Record 10 blanks here.
RAIN(L)	G10.0	Strength of an areally distributed source of water (Volume/sec)/(Unit Area of Aquifer) = (Length/sec), defined as a constant over element L. In an unconfined aquifer element this may, for example, be recharge rate expressed as (depth of accumulated rainwater which infiltrates per sec).

-------------------- Data Set 12: Nodal Incidence in Elements------------------

(one card for each element in the mesh, NE cards)

L	I5	Element number.
CHAR	Free Format	Special ordered list of node numbers in element L. The node numbers are listed beginning with any corner node and proceeding counter-clockwise around the element and finally repeating the first corner node number. The positions of element sides are indicated by setting a star (or asterisk) immediately after each corner node number. At least one blank must appear between each entry in the list.



For the example element to the left, the list may appear as follows:

8* 4 2* 1* 3 5* 6 7 8*

-------------------- Data Set 13: Constant Hydraulic Head Nodes -----------

LRT	20I4	Node number of nodes where hydraulic head is specified as a fixed constant. Before an extra card is included, 20 node numbers must be recorded on the previous card. In total, there must be exactly NS node numbers specified. The last card need not have 20 numbers.

----------------------- {Data Set 14: Elementwise Effective Porosity and Aquifer Thickness for Velocity Calculations.}
(One card for each element, NE cards).

POR(L)	G10.0	Effective porosity for flow defined as a constant value over element L.
AQTHK(L)	G10.0	Aquifer thickness defined as a constant value over 'confined' element L.
		AQTHK(L) need be specified only in 'confined' aquifer elements.
		If nodewise velocity is not to be calculated (KOD11=0) then this data set is OMITTED.

-------------------- {Data Set 15: Leaky Aquifer Elements} -----------------

Card (1)

HYCOND	F15.0	Hydraulic conductivity in Length/second of semi-confining layer in all leaky aquifer elements.
SS	F15.0	Specific storage coefficient in 1/Length of semi-confining layer in all leaky aquifer elements. Setting SS to zero yields steady-state leakage in all leaky elements.

Cards(2) through (NL+1) (one card for each leaky aquifer element, NL cards)

I	I5	Element number of leaky aquifer element.
THK(I)	G10.0	Thickness of semi-confining layer either above or below aquifer in element I.
HZERO(I)	G10.0	Hydraulic head (unchanging in time) of the adjacent aquifer on the other side of the semi-confining layer in element I.
		If there are no leaky aquifer elements (NL=0), this data set is OMITTED.

--------------------- {Data Set 16: Plotting Information }-----------------

If no plot is requested (KOD6=0, KOD7=0, and KOD12=0) then this data set is OMITTED.

Card (1)		Name(s) of the plot(s) requested separated by a blank. The three possible names are HEAD for hydraulic head plot, DRAWDOWN for hydraulic head drawdown plot, and VELOCITY for groundwater velocity magnitude and direction plots.
Card (2, {3,4})		(one card for each plot requested)
		Labels for axes and plot title are provided separately for each plot requested in the same order that the plot names are listed on Card (1).
XLABEL	16A1	Label for vertical axis of plot.
YLABEL	24A1	Label for horizontal axis of plot (across output paper).
TATLE	40A1	Title for plot.
Next to Last Card		(plotting dimension parameters)
XMAX	G10.0	Highest value on vertical axis. Should be somewhat greater than largest coordinate value of a node (given by FACTX*X(I) or FACTY*Y(I) of the coordinate that is to be plotted along the length of the output.)

XMIN	G10.0	Lowest value on vertical axis. Should be somewhat lower than lowest coordinate value a node of the coordinate which is to be plotted along the length of the output paper.
NXS	I10	Number of segments vertical direction is to be divided into by lines drawn on the graph. If NXS=1 no grid lines will be drawn across the output paper within the plotted region.
NINX	I10	Number of (inches) in vertical grid segment. NXS*NINX is the actual length of the vertical axis in inches.
YMAX	G10.0	Same as XMAX but for coordinate direction which is to be plotted along the width of output paper (horizontal).
YMIN	G10.0	Same as XMIN but for horizontally plotted coordinate.
NYS	I10	Same as NXS but for horizontally plotted coordinate.
NINY	I10	Same as NIX but for horizontally plotted coordinate. NYS*NINY must be less than the width of the output paper.
Last Card		(Plotting control parameters).
KKKKK	I10	Plot direction control. Allows longest of NXS*NINX and NYS*NINY to be plotted along length of output paper so that the largest plotting scale may be used. If KKKKK=1 the x-axis is plotted along the length of the output paper (vertically). If KKKKK=-1 the y-axis is plotted along the length of the output paper (vertically).

CMAX	G10.0	Significant figure control for hydraulic head plot.
ADDN	G10.0	Significant figure control for drawdown plot.
AVV	G10.0	Significant figure control for velocity magnitude plot.
AVA	G10.0	Significant figure control for velocity direction plot (set AVA=0.010).

The plotter writes only three digits of the plottted variable at each node coordinate; these are: one digit to the left of the decimal point and two digits to the right of the decimal point. The preceding four variables (CMAX, ADDN, AVV, AVA) should be chosen so that the digits of interest in the plot (usually the first three significant figures) when multiplied by the appropriate significant figure control fall into the positions which are written by the plotter.

For example, the velocity direction values may go up to 360°. A particular angle: 347.541° would be written on the plot as:

541 for AVA = 10.00
754 for AVA = 1.000
475 for AVA = 0.100
347 for AVA = 0.010
034 for AVA = 0.001

Thus a value of AVA = 0.010 will always write the number of degrees truncated at the decimal point.

Note that the significant figure control for plots that are not requested may be left blank.

--------------------- Data Set 17: Completion of Data File -----------------

CARD	20A4	The letters XXXX must be punched in columns 1-4 to indicate the conclusion of the data file. The remaining 76 positions may be used for a message or may be left blank.