**UNIVERSITY OF CALIFORNIA**

**Los Angeles**

# Finite Difference Simulation of the Charnock Sub-Basin Hydrology

A thesis submitted in partial satisfaction of the requirements for the degree of Master of Science in Engineering

by

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1985

The dissertation of John E. Hoagland is approved.

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1985

This thesis is dedicated to Kathy for her patience and to my father and mother for their encouragement over the years.

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# Acknowledgements

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## ABSTRACT OF THE THESIS

Finite Difference Simulation of
the Charnock Sub-Basin Hydrology

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Master of Science
University of California, Los Angeles, 1985
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The Charnock sub-basin is the principle source of local water supply for the City of Santa Monica and a supplemental source of water for the City of Culver City, both located in the western portion of the Los Angeles coastal plain. The simulation created by this thesis attempts to quantitate the sources which recharge the Charnock sub-basin including the possible inflow of sea water through continuous aquifers in the Ballona Gap area. Several scenarios which represent possible pumping conditions for the sub-basin are examined for their effect on the 'hydrologic' topography of the sub-basin. The simulation was unable, however, to reproduce the historical overdraft conditions. This inability could be due to the veracity of historical information regarding the recharge rate to the study area and historical pumping rates, the permeability of the boundary faults or the assumptions regarding aquifer

parameters or a combination of all these factors.

# INTRODUCTION

The purpose of this thesis is to create a numerical model which will describe the hydraulic characteristics of the Charnock sub-basin. The simulation will be useful in studying the water quality aspects of the basin at a future time.

The aquifers within the Charnock sub-basin are the principle source of local water supply for the City of Santa Monica and a supplementary water supply for the City of Culver City. (Note that the Culver City water system is operated by the Southern California Water Company.)

The sub-basin has provided continuous, reliable water supplies since the first deep wells were drilled in the late 1800's. Withdrawals have ranged as high as 13,000 acre-feet per year (11.4 MGD) in 1940, (Poland, 1959) and are currently 7,000 acre-feet per year (6.1 MGD) (Santa Monica, 1983) of which 5,740 AF/Y (5.0 MGD) is produced by Santa Monica to meet 33% of its average daily demand and 1.1 MGD is produced the Southern California Water Company to meet 10% of the average daily demand for the City of Culver City. Although during the past 90 years there have been many small pumpers, currently there are no other known pumpers in the Charnock sub-basin.

The basin is located on the Los Angeles coastal plain (Figure 1) and is overlain by residential and commercial property. The geology of the area prevents surface observation of the basin boundaries (Figure 2). The boundaries, however, are very regular with the east and west (nominal) sides bounded by the Overland and Charnock faults respec-

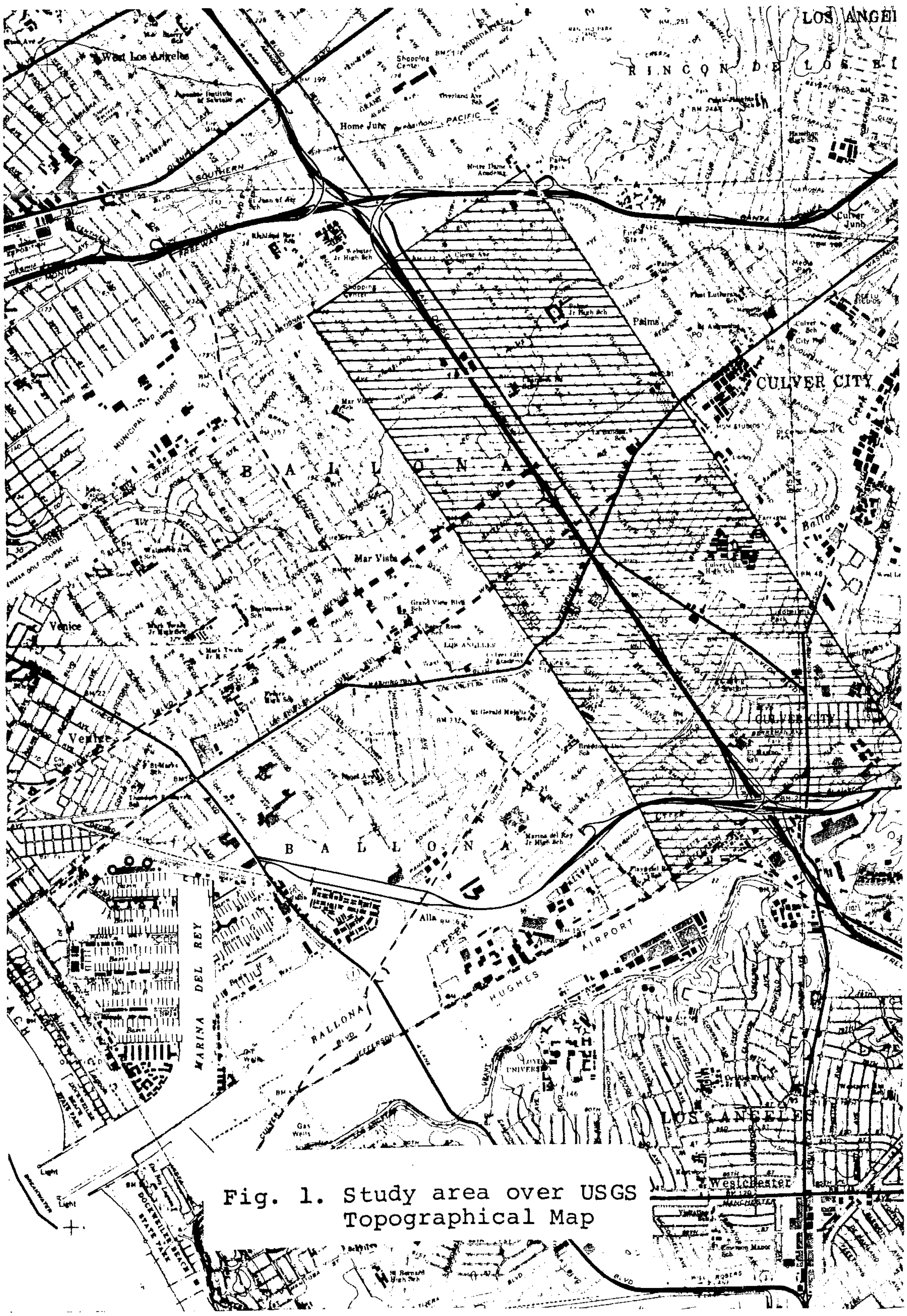


Fig. 1. Study area over USGS Topographical Map


Fig. 2. Study area over USGS Geological map

tively, which are parallel to each other and parallel to the Newport Inglewood fault further east (Poland, 1959). The northern boundary of the aquifer is the south flank of the Santa Monica mountains, but it is not well defined geologically, while on the south there is no apparent boundary, the sub-basin becomes continuous with the West basin of Los Angeles county (Poland, 1959). The area simulated is bounded by the Charnock and Overland faults, National Blvd. and approximately Jefferson Blvd. (Figure 2). The dimensions of the study area are 6,600 feet between the faults, 17,600 feet between the boulevards and to a depth of approximately 400 feet below the surface (Figure 3) which represents a volume of .31 cubic miles and an area of 4.17 square miles. The regular, rectangular shape of the Charnock sub-basin is ideal for a finite difference simulation due to the rectangular shape of the finite difference blocks (Figure 4).

The most serious potential problem which can result from the use of the Charnock sub-basin is sea water intrusion due to the proximity of the sub-basin to Santa Monica Bay (3.125 miles west of the Charnock Fault). Fortunately, the Charnock (and Overland) fault appears to be an excellent groundwater barrier (Poland, 1959), probably due to cementation of deposits along the slipfront. In spite of the apparent impermeability of the Charnock fault, water described as 'salty' was measured as far north as Washington Boulevard in 1945. The inflow was probably due to extensive withdrawals by Santa Monica and the Southern California Water Company during period from 1935 to 1944 when withdrawals averaged 9,603 acre-feet per year (Poland, 1959), exceeding the average normal recharge rate of 7,000 AF/Y by 2,603 AF/Y (or 37%).

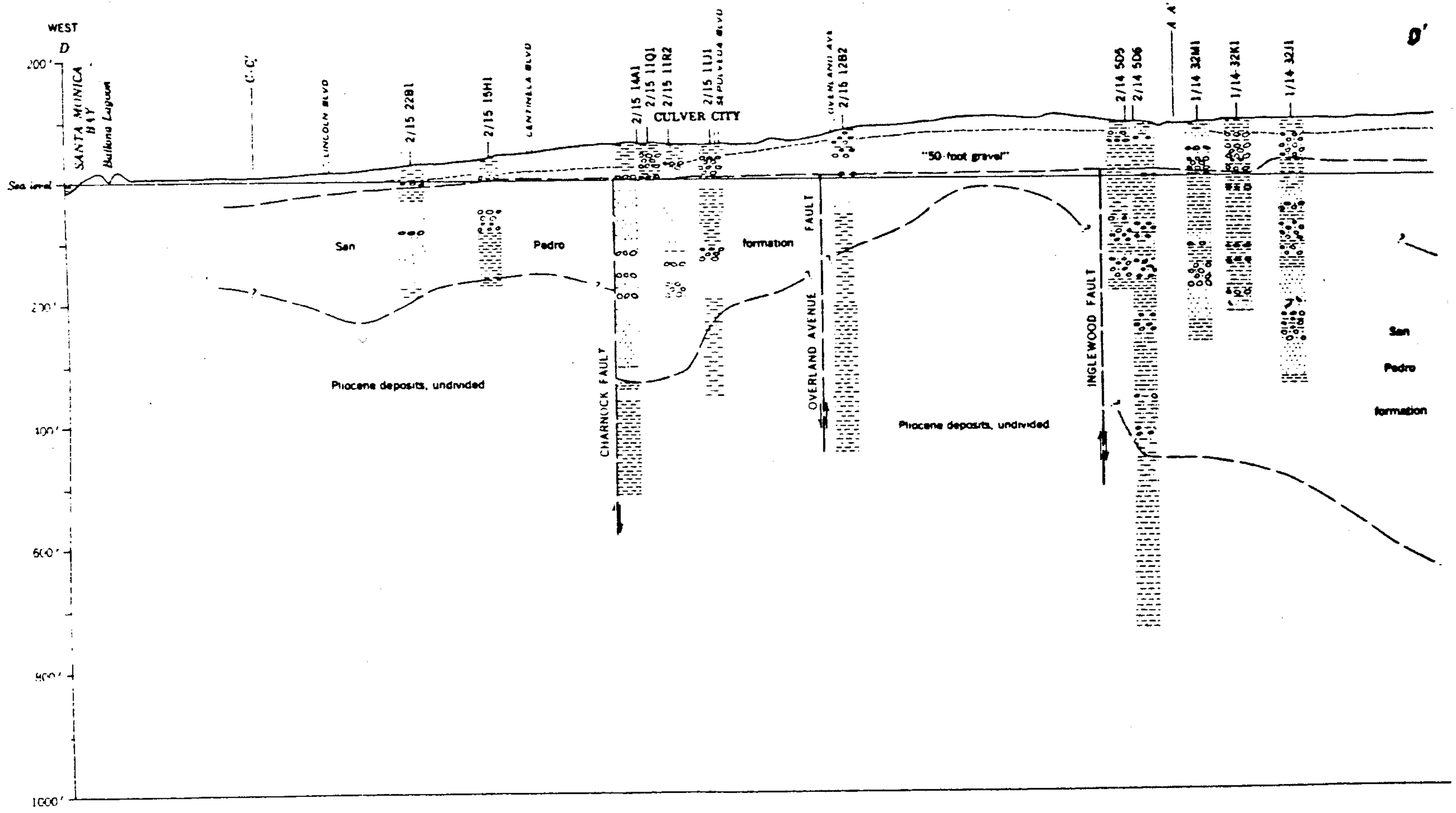


Fig. 3. From Fig 2. (source Poland, 1959)     SECTION D-D' THROUGH BALLONA GAP

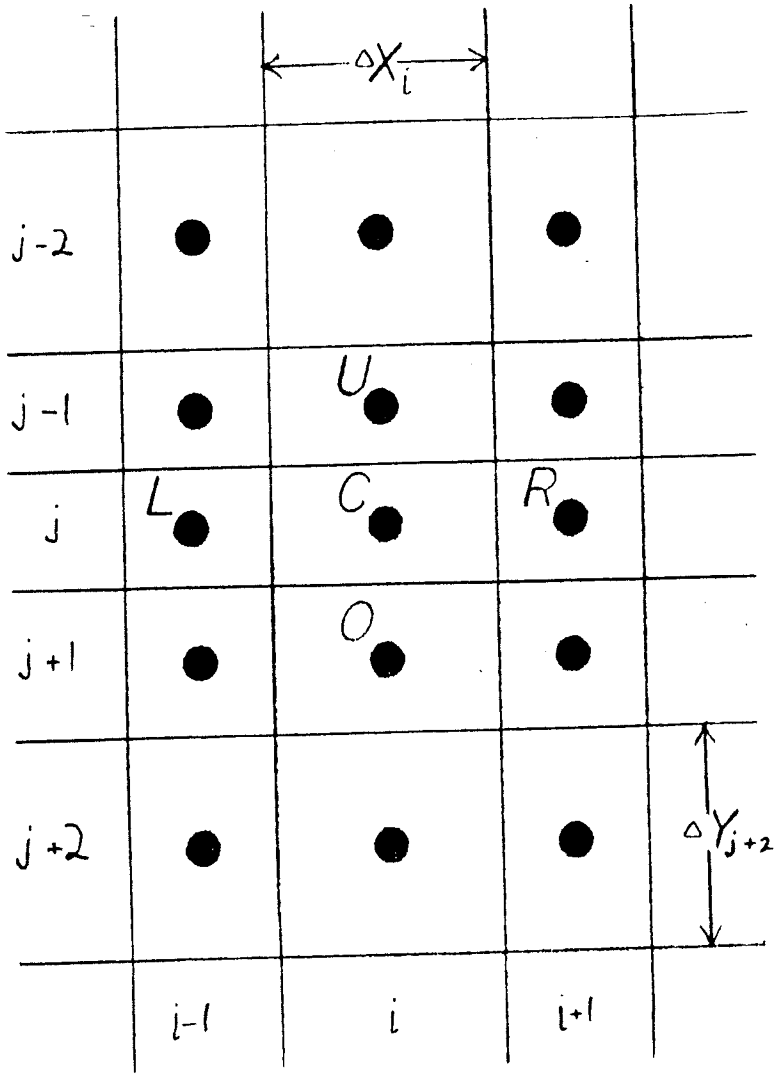


Fig. 4. Finite difference blocks of model

The simulation of the hydraulic gradients which could result in saline inflow to the Charnock sub-basin is the purpose of this paper.

## LITERATURE REVIEW

The finite difference approach to the solution of partial differential equations has been available since the early 1940's and was summarized by Southwell (1946). The procedures languished for several years, however, since the technique requires a very large number of arithmetic calculations which render even simple problems prohibitively time consuming if done manually. Terwilliger et al. (1951) first applied the numerical solution techniques to a porous media flow problem concerning the gravity drainage of an oil reservoir, using a punch card system. The Alternating Direction Implicit (ADI) method for the solution of non-linear partial differential equations was first applied to porous media by Bruce et al. (1953) in studying linear and radial gas flow. The general applicability of the ADI method to the solution of elliptical and parabolic partial differential equations was described by Peaceman and Rachford (1955).

The potential of the ADI method for the solution of multidimensional Laplace equations as applied to studying the steady-state hydrodynamics of large scale geologic basins was noted by Fagas and Sheldon (1962). The use of such a numerical technique to evaluate the non-steady-state response of an aquifer to pumping stress was done by Fiering (1964), but his equations required restrictive criteria which resulted in an uneconomical procedure (in terms of computer time) when applied to long term response of large aquifer with high transmissivities and small storage coefficients. A more satisfactory technique for the long term evaluation of an aquifer stress response to pumping was described by Eshett and Longenbaugh (1965), it included the use of the ADI scheme for the solution of the finite difference approximations arising from a two dimensional non-linear, second order partial differential equation describing the homogeneous isotropic aquifer flow. Pinder and Bredehoeft (1968) proposed a generalized model for evaluating confined aquifer hydrology and Bredehoeft and Pinder (1970) simulated a three dimensional series of aquifers including an unconfined aquifer using a series of two dimensional models coupled by leakage factors. Trescott et al. (1976) created a standardized finite-difference model for the United States Geological Survey for two dimensional aquifer simulation including a combination of an unconfined and confined aquifers.

Finite element simulations, as exemplified by Pinder and Frind (1972) became popular in the early 1970's, because of their utility in simulating irregularly shaped areas. The ability to simulate regular or irregular areas drew attention to the weakest segment of simulation, the study area parameters. In most cases, a large study area is characterized by only a few observation points from which all of the parameter data must be derived.

An attempt to determine the values of the component parameters of a study area using the performance or observational data of the area is called inverse problem solution or parameter identification. Several methods of parameter identification (the determination of the parameters of a distributed system governed by partial differential equations) are numerically illustrated by Yeh (1975) and the field surveyed by Kubrusly

(1977). Yeh and Yoon (1981) showed that the parameters identified can be improved using covariance analysis to determine the optimal dimensions for parameterization. Yeh, Yoon and Lee (1983) proposed a modification of the direct approach (Sagar et al., 1975) in which unknown head values are spatially interpolated using kriging (Delhomme, 1979), the instability and nonuniqueness problems are controlled by reparameterization thus eliminating iterative solutions of the governing equations and covariance analysis is used to determine the optimum parameter dimension.

The Charnock sub-basin is a regular shaped area (rectangle) and the two aquifers are continuous which allow for the application of finite-difference approximations to the governing flow equations.

## EQUATIONS OF GROUNDWATER FLOW

Pinder and Bredehoeft have described the partial differential equation for transient flow in a confined aquifer as

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right)$$

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

(Pinder and Bredehoeft, 1968)

where

| | | |
|---|---|---|
| $T_{xx}$, $T_{xy}$, $T_{yx}$, $T_{yy}$ | = | components of the Transmissivity Tensor |
| h | = | the hydraulic head |
| S | = | the storage coefficient |
| W(s,y,t) | = | the volumetric flux of recharge or withdrawal per unit surface area of the aquifer |

The equation may be simplified by assuming that the cartesian coordinates lie in the same direction as the principle transmissivity tensors $T_{xx}$ and $T_{yy}$:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad (2)$$

Since the Charnock sub-basin is not confined, the transmissivity is a function of the hydraulic head:

$$T_{yy} = K_{yy}b$$

$$T_{xx} = K_{xx}b$$

where

| | | |
|---|---|---|
| $K_{yy}$ and $K_{xx}$ | = | the principle hydraulic conductivity tensors |
| b | = | saturated thickness of the aquifer |

If the cartesian coordinates are assumed to be aligned with the principle hydraulic conductivity tensors and the above terms substituted, the resulting equation is:

$$\frac{\partial}{\partial x}\left(K_{xx}b\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}b\,\frac{\partial h}{\partial y}\right) = S_y\,\frac{\partial h}{\partial t} + W(x,y,t) \tag{3}$$

where

$S_y$ = the specific yield of the unconfined aquifer.

The algorithm in the simulation is based on the transmissivity which is calculated before each time step from:

$$T_{i,j,m} = K_{i,j} * h_{i,j,m-1}$$

where

| | | |
|---|---|---|
| $T_{i,j,m}$ | = | the transmissivity in block i,j at time step m |
| $K_{i,j}$ | = | the hydraulic conductivity in block i,j (given) |

$h_{i,j,m-1}$ = the hydraulic head at node i,j from the previous time step

Thus the governing equation to which the finite difference analogs are to be applied is:

$$\frac{\partial}{\partial x}\left\{T_{xx}\frac{\partial h}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{T_{yy}\frac{\partial h}{\partial y}\right\} = \frac{Sy\partial h}{\partial t} + W(x,y,t) \qquad (4)$$

The strictly implicit finite difference analogs based on a block-centered finite difference grid (Figure 4) (Von Rosenberg, 1969) are:

$$\frac{\partial}{\partial x}\left\{T_{xx}\frac{\partial h}{\partial x}\right\} = \frac{1}{\Delta x_i}\left\{\left[T_{xx(i+1/2,j)}\frac{(h_{i+1,j,k} - h_{i,j,k})}{\Delta x_{i+1/2}}\right] - \left\{\left[T_{xx(i-1/2,j)}\frac{(h_{i,j,k} - h_{i-1,j,k})}{\Delta x_{i-1/2}}\right]\right\}\right.$$

$$\frac{\partial}{\partial y}\left\{T_{yy}\frac{\partial h}{\partial y}\right\} = \frac{1}{\Delta y_j}\left\{\left[T_{yy(i,j+1/2)}\frac{(h_{i,j+1,k} - h_{i,j,k})}{\Delta y_{j+1/2}}\right] - \left[T_{yy(i,j-1/2)}\frac{(h_{i,j,k} - h_{i,j-1/2,k})}{\Delta y_{i-1/2}}\right]\right\}$$

$$Sy\frac{\partial h}{\partial t} = \frac{S_{i,j}(h_{i,j,k} - h_{i,j,k-1})}{\Delta t}$$

$$W(x,y,t) = \frac{Q_{i,j}}{\Delta x_i\ \Delta y_j}$$

where

$\Delta x_i$ = the space increment in the x direction

$\Delta y_j$ = the space increment in the y direction

$\Delta t$ = the time increment

| | | |
|---|---|---|
| $i$ | = | the index in the x direction |
| $j$ | = | the index in the y direction |
| $k$ | = | the index in the time direction |
| $T_{xx(i+1/2,j)}$ | = | the transmissivity between node (i,j) and node (i+1,j) |
| $\Delta x_{i+1/2}$ | = | the distance between node (i,j) and node (i+1,j) |
| $Q_{i,j}$ | = | the net discharge (+) or recharge (-) for node (i,j) |

In order to insure continuity across cell boundaries at steady state with a variable grid and make coefficients zero at no flow boundaries the harmonic mean is used to represent the ratio of $T_{xx(i+1/2,j)}/\Delta x_{i+1/2}$ (Stone, 1968). As an example the Harmonic Mean of $\frac{T_{xx(i,j)}}{\Delta x_i}$, $\frac{T_{xx(i+1,j)}}{\Delta x_i+1}$ is $\frac{2T_{xx[i,j]}T_{xx[i+1,j]}}{T_{xx[i,j]}\Delta x_{i+1} + T_{xx[i+1,j]}\Delta x_i}$. Substitution of the finite difference analogs and utilization of the Harmonic Mean results in the simplified equation:

$$\frac{R_{i,j}}{\Delta x_i}\left(h_{i+1,j,k} - h_{i,j,k}\right) - \frac{L_{i,j}}{\Delta x_i}\left(h_{i,j,k} - h_{i-1,j,k}\right)$$

$$+ \frac{O_{i,j}}{\Delta y_j}\left(h_{i,j+1,k} - h_{i,j,k}\right)$$

$$- \frac{U_{i,j}}{\Delta y_j}\left(h_{i,j,k} - h_{i,j-1,k}\right)$$

$$= \frac{S_{i,j}}{\Delta t}\left(h_{i,j,k} - h_{i,j,k-1}\right) + \frac{Q_{i,j}}{\Delta x_i \Delta y_j} \tag{5}$$

where

$$R_{i,j} = \left[\frac{2T_{xx[i,j]}T_{xx[i+1,j]}}{T_{xx[i,j]}\Delta x_{i+1} + T_{xx[i+1,j]}\Delta x_i}\right]$$

$$L_{i,j} = \left[\frac{2T_{xx[i,j]}T_{xx[i-1,j]}}{T_{xx[i,j]}\Delta x_{i-1} + T_{xx[i-1,j]}\Delta x_i}\right]$$

$$U_{i,j} = \left[\frac{2T_{yy[i,j]}T_{yy[i,j-1]}}{T_{yy[i,j]}\Delta y_{j-1} + T_{yy[i,j-1]}\Delta y_j}\right]$$

$$O_{i,j} = \left[\frac{2T_{yy[i,j]}T_{yy[i,j+1]}}{T_{yy[i,j]}\Delta y_{j+1} + T_{yy[i,j+1]}\Delta y_j}\right]$$

(see Figure 4 for the block centered variable grid representation)

Expanding and collecting the terms:

$$h_{i,j,k}\left[\frac{-R_{i,j}}{\Delta x_i} - \frac{L_{i,j}}{\Delta x_i} - \frac{O_{i,j}}{\Delta y_j} - \frac{U_{i,j}}{\Delta y_j} - \frac{S_{i,j}}{\Delta t}\right]$$

$$+ h_{i+1,j,k}\left[\frac{R_{i,j}}{\Delta x_i}\right] + h_{i-1,j,k}\left[\frac{L_{i,j}}{\Delta x_i}\right]$$

$$+ h_{i,j+1,k}\left[\frac{O_{i,j}}{\Delta y_j}\right] + h_{i,j-1,k}\left[\frac{U_{i,j}}{\Delta y_j}\right]$$

$$= \frac{-S_{i,j}}{\Delta t}(h_{i,j,k-1}) + \frac{Q_{i,j}}{\Delta x_i\ \Delta y_j} \tag{6}$$

Equation (6) if the finite difference analog of the governing equations (4).

Using the alternating direction implicit (ADI) procedure (Von Rosenberg, 1969) equation (6) can be converted into the column and row implicit forms for ADI as follows:

-Row implicit equation-

$$
\begin{aligned}
& h_{i,j,k}\left[\frac{-R_{i,j}}{\Delta x_i} - \frac{L_{i,j}}{\Delta x_i} - \frac{O_{i,j}}{\Delta y_j} - \frac{U_{i,j}}{\Delta y_j} - \frac{S_{i,j}}{\Delta t}\right] \\
& + h_{i+1,j,k}\left[\frac{R_{i,j}}{\Delta x_i}\right] + h_{i-1,j,k}\left[\frac{L_{i,j}}{\Delta x_i}\right] \\
& = -h_{i,j,k-1}\left[\frac{S_{i,j}}{\Delta t}\right] + \frac{Q_{i,j}}{\Delta x_i \Delta y_j} \\
& - h_{i,j-1,k-1}\left[\frac{U_{i,j}}{\Delta y_j}\right] - h_{i,j+1,k-1}\left[\frac{O_{i,j}}{\Delta y_j}\right] \qquad (7)
\end{aligned}
$$

-Rearranging-

$$A_{(i)}h_{(i-1,j,k)} + B_{(i)}h_{(i,j)} + C_{(i)}h_{(i+1,j,k)} = D_{(i)} \qquad (8)$$

where

$$A\ (i) = L_{i,j}/\Delta x_i$$

$$B\ (i) = -R_{i,j}/\Delta x_i - L_{i,j}/\Delta x_i - O_{i,j}/\Delta y_j - U_{i,j}/\Delta Y_j - S_{i,j}/\Delta t$$

$$C\ (i) = R_{i,j}/\Delta x_i$$

$$D\ (i) = Q_{i,j}/\Delta x_i \Delta y_j - h_{i,j,k-1}\left[S_{i,j}/\Delta t\right]$$

$$- h_{i,j-1,k-1}\left[U_{i,j}/\Delta y_j\right]$$

$$- h_{i,j+1,k-1}\left[O_{k,j}/\Delta y_j\right]$$

-Similarly the column explicit equation-

$$A_{(j)}h_{(i,j-1,k)}+B_{(j)}h_{(i,j,k)}+C_{(j)}h_{(i,j+1,k)} = D_{(j)} \tag{9}$$

where

$$A\ (j) = U_{i,j}/\Delta y_j$$

$$B\ (j) = -R_{i,j}/\Delta x_i - L_{i,j}/\Delta x_i - O_{i,j}/\Delta y_j$$

$$- U_{i,j}/\Delta y_j - S_{i,j}/\Delta t$$

$$C\ (j) = O_{i,j}/\Delta y_j$$

$$D\ (j) = Q_{i,j}/\Delta x_i \Delta y_j - h_{i,j,k-1}\left[S_{i,j}/\Delta t\right]$$

$$- h_{i+1,j,k-1}\left[R_{i,j}/\Delta x_i\right]$$

$$- h_{i-1,j,k-1}\left[L_{i,j}/\Delta x_i\right]$$

The row implicit equation is applied to each row of n grid points of the finite difference grid at time step k and results in a set of n equations which in matrix form

$$R\ h = \overline{D}\ (j)$$

can be solved by the Thomas algorithm (Von Rosenberg, 1969). (The matrix R is tridiagonal in structure with A(j), B(j), and C(j) the non-zero terms in the jth row of the matrix.) The resulting h (hydraulic head) values are tabulate row by row and become the k+1 time step. The column implicit equation is applied to each ith column of the finite difference grid at the k+1 time step, the Thomas algorithm is again used to find the h values for each ith column. The values are tabulated and the result is the finite approximation of the head values at the k+2 time step. Note that the head values at the k+1 time step are an artifact of the ADI procedure and may not have physical significance. Only k+2 head values which are the result of a complete ADI step are reported by the simulation.

The ADI procedure is unconditionally stable if the $\Delta x$, $\Delta y$ and $\Delta t$ values are kept constant within each complete ADI step (Von Rosenberg, 1968).

## GEOLOGY-HYDROLOGY OF THE MODEL AREA

The geology of the Charnock sub-basin water bearing strata is relatively uncomplicated. There are two distinct water bearing strata, the San Pedro formation and the '50 foot gravel.' The San Pedro formation is a thick (200-350 feet) Pleistocene deposit of sands and gravels interspaced with silt and clay lenses. It was deposited before the beginning of the geosyncline deformation of what is now the West Basin and therefore shows the displacement of the faults and the resulting dropped block character of the sub-basin (Figure 5). The San Pedro formation appears to underly the entire study area (Poland, 1959).

The '50 foot gravel' by contrast is a recent deposit and does not show the slipfronts of the faults. It is composed primarily of fine gravel and course sand and underlies only that portion of the study area which is below the Ballona Gap (Figures 3 and 5).

The 50 foot gravel was extensively tapped early in the century for domestic and irrigation use but was abandoned by the end of the 1940's due to the declining water levels and saline water intrusion. The San Pedro formation was first utilized in the 1920's and developed as the primary aquifer for the area due to its high yields and continued quality in spite of tremendous drawdowns. The expense of constructing and operating the required deep wells limited the number of operators and in 1983, only Santa Monica and the Southern California Water Company are actively pumping in the Charnock sub-basin.

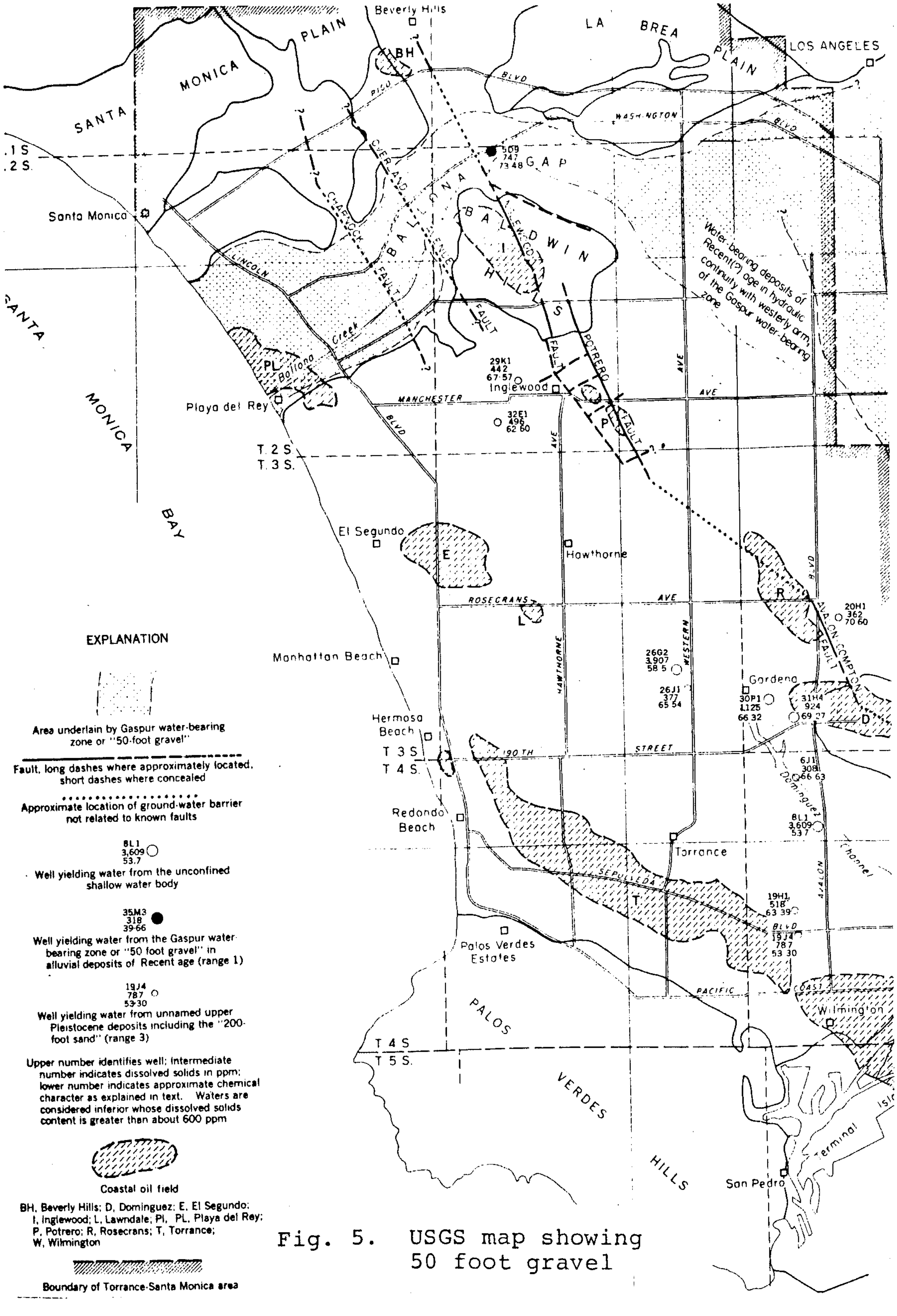


Fig. 5. USGS map showing 50 foot gravel

As mentioned previously, Poland (1959), inferred that the boundary faults are effective groundwater barriers because water levels differing by from 50 to 90 feet could be found during a 1930's–1940's survey period on differing sides of the faults. During most of these earlier survey periods, however, extensive pumping was occurring not only in the Charnock sub-basin but also in the adjoining sub-basins such that the water levels were generally below the 50 foot gravel (the 50 foot gravel was dewatered). The 50 foot gravel appears to be continuous with the San Pedro formation (inferred from the dewatering of the 50 foot gravel with the development of the San Pedro Formation in the 1930's and 40's).

The 1983, pumping situation is different, however, because there are no known active pumpers in the coastal sub-basin and only Metro-Goldwyn-Meyer in the crestal sub-basin to the east is still active (900 gpm).

Water levels from Los Angeles County Flood Control records and from industries in the westerly Ballona Gap (Hughes Helicopters and Southern California Gas Company) show 1983, water levels above sea level six to eight feet. Levels in the crestal basin to the east, however, are not determinable because of the lack of observation points.

An interpretation of this information is that while the San Pedro Formation does not allow interbasin transfer of groundwater due to the Charnock and Overland faults, the 50 foot gravel formation which is not intersected by the faults can provide interbasin transfer of groundwater when the appropriate hydraulic gradients exist. Current pumping in the crestal basin is possibly dewatering the 50 foot gravel eliminating the gradients which would result in interbasin transfer on the east side of the study area. On the west side of the study area the 50 foot gravel extends below sea level. The current water level in the coastal basin is six to eight feet above sea level creating a five to 30 foot window through which recharge can occur, the rate being dependent on the hydraulic gradient.

The extent of salt water intrusion in 1945, as shown in Figure 6, is further evidence that the path of inflow of saline water is eastward along the Ballona Gap from the Pacific Ocean. The saline water appears to have been transferred across the basin boundary through the 50 foot gravel and the extensive overdraft of the Charnock sub-basin during that period provided the gradient for northward flow of the saline water to approximately Washington Place.

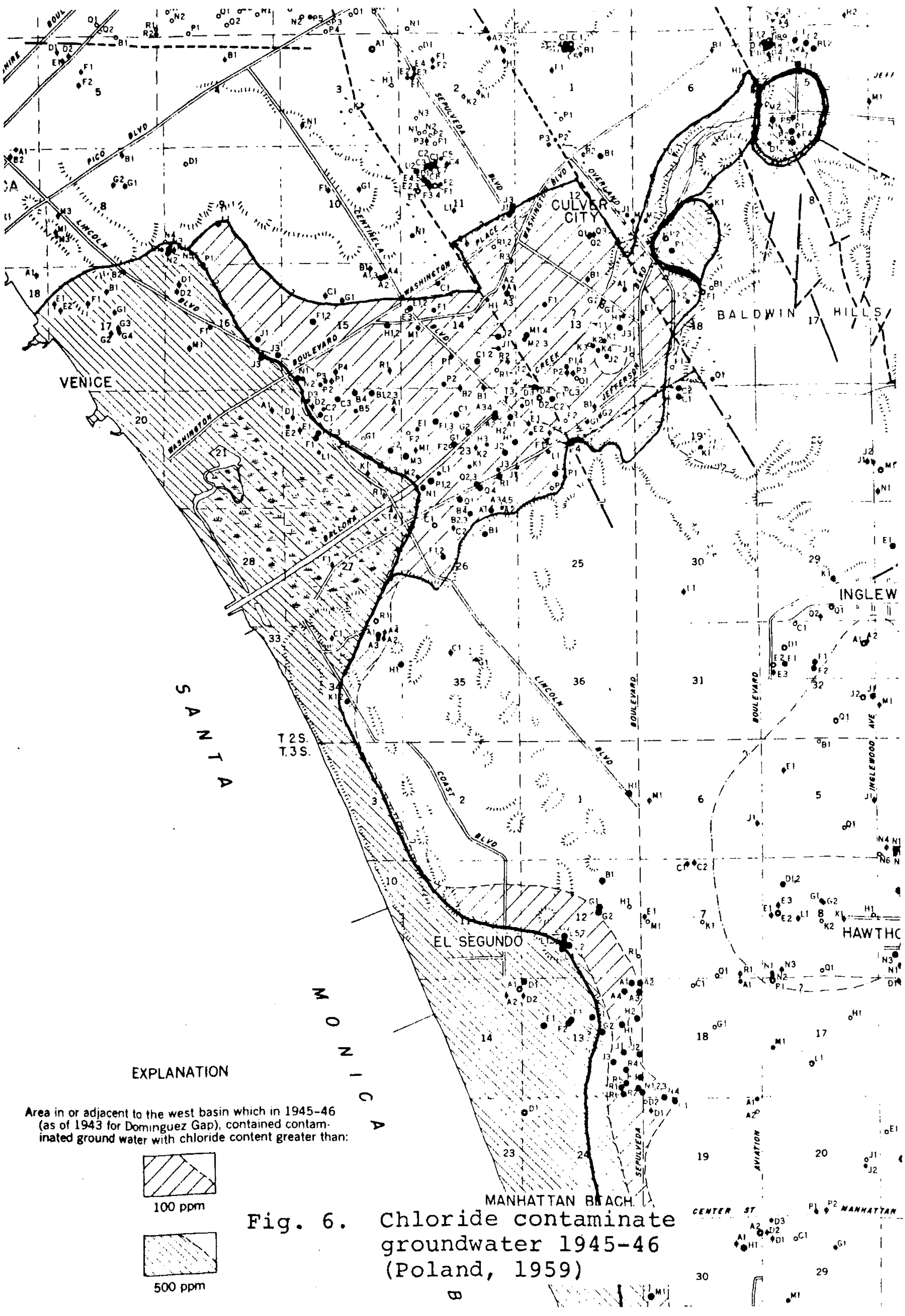


Fig. 6. Chloride contaminate groundwater 1945-46 (Poland, 1959)

## DETERMINATION OF MODEL PARAMETERS

Since the actual study area is rectangular in shape the model area is easily constructed for the finite difference simulation. A rectangle with 43 columns and 76 rows is defined with the dimensions of the blocks listed in Table 1 and shown in Figure 7.

TABLE 1

Dimensions of the finite difference blocks

Column Dimensions (X)

| X Index | Dimension (feet) | X Index | Dimension (feet) |
|---|---|---|---|
| 1-24 | 100 | 28-31 | 200 |
| 25 | 125 | 32-36 | 250 |
| 26 | 150 | 37-43 | 300 |
| 27 | 175 | | |

Row Dimensions (Y)

| Y Index | Dimension (feet) | Y Index | Dimension (feet) |
|---|---|---|---|
| 1-5 | 300 | 40-41 | 150 |
| 6-10 | 250 | 42-44 | 200 |
| 11-13 | 200 | 45-49 | 250 |
| 14-15 | 150 | 50-54 | 300 |
| 16-17 | 125 | 55-60 | 350 |
| 18-37 | 100 | 61-76 | 400 |
| 38-39 | 125 | | |

The construction of the model area in this manner allows for a larger number of blocks of smaller area in the vicinity of the withdrawal and artificial recharge activity. Experience has shown (Trescott et al., 1976) that the expansion of the finite difference grid will not present problems of large truncation errors and convergence when the restriction

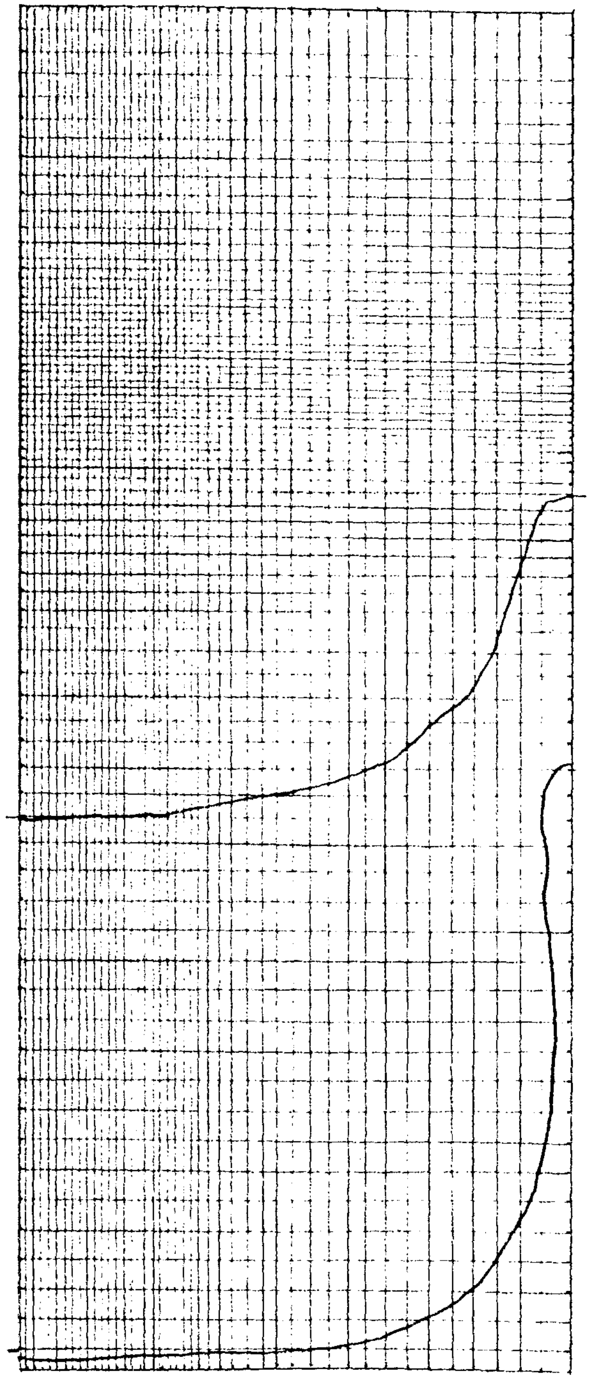

Fig. 7. Study area showing finite difference grid. + 50' gravel

of the ratio DX(J)/DX(J-1) $\leq$ 1.5 is maintained. Table 1 shows that this restriction has been met for this model. The location of the wells is from survey data and maps of the area and the flow rates are from production data of the City of Santa Monica and the the Southern California Water Company. Table 2 is a summary of the block assignments of the wells, their discharge rates for the initial calibration of the model and the heads of the static wells in terms of height above the base of the aquifer.

Table 2

Well Data for the Model Area

| Well | Location DX | Location DY | Flow Rate (Cu.Ft./day) | Head (feet) |
|---|---|---|---|---|
| SoCal #8 | 8 | 31 | +144,385 | ---- |
| SoCal #9 | 7 | 31 | STATIC | 198. |
| SM 7 | 14 | 26 | STATIC | 194. |
| SM 9 | 19 | 24 | STATIC | 185. |
| SM 12 | 16 | 23 | +133,680 | ---- |
| SM 13 | 17 | 26 | STATIC | 196. |
| SM 14 | 15 | 26 | STATIC | 192. |
| SM 15 | 12 | 25 | +174,417 | ---- |
| SM 16 | 19 | 22 | +439,316 | ---- |
| SM 17 | 11 | 24 | STATIC | 193. |

NOTE: (+) VALUES ARE WITHDRAWALS, (-) VALUES ARE RECHARGE

The intermittent pumping of well SM 12 is treated as a constant pumping well of the total daily discharge of the well.

The specific yield and hydraulic conductivity for the area were determined from pumping test data of the City of Santa Monica which tested the Charnock well field in April, 1982 (City of Santa Monica, Internal Memoranda, 1982). The hydraulic conductivity and specific yield data were extended to the rest of the Charnock sub-basin for the model use, although no actual data for the Ballona Gap area is available.

The initial head values represent the initial saturated thickness of the aquifer and were determined from geologic cross-sections and well logs of the sub-basin (Poland, 1959 and L.A. County Flood Control District, 1983).

The recharge to the area is principally from the northern boundary (67% or 4. MGD) and secondarily from the southern boundary (33% or 2. MGD). This is distributed among the blocks based on their area. Precipitation recharge is based on an assumption of 12 inches per year or 0.00274 feet/sq.ft./day and is allocated to each block based on area. Recharge from the adjacent crestal and coastal sub-basins is determined through an iterative process comparing the drawdown along the boundaries with the original water level, if water levels decrease more than an arbitrary criteria (two feet) then a recharge flow is determined from the following adaptation of Darcy's Law and is allocated to the recharge block:

$$Q = Qdf + (-Kdf*FFG*DY*DWDN)/DX$$

where

| | | |
|---|---|---|
| Q | = | the net recharge (-) or discharge (+) of the block |
| Qdf | = | the default recharge to the block from precipitation |
| Kdf | = | the default hydraulic conductivity for the block |
| FFG | = | the thickness of the saturated 50 foot gravel in the block |
| DY | = | the length of the block |
| DWDN | = | the calculated drawdown at the block |
| DX | = | the width of the block |

This treatment for inflow through the 50 foot gravel is done only in the areas where the 50 foot gravel overlays the sub-basin (i.e., in the Ballona Gap which on the east side is blocks J=42 to 60 and on the west block J=58 to 75, (see Figure 7).

# COMPUTER MODEL

The model program is written in FORTRAN and a listing appears as Appendix A.

The main program handles the tasks of reading the input data, calculating the initial simulation parameters, creating an output heading, calculating the transmissivities for each time step, preforming the row and column calculations, iterating for both ADI head level convergence and 50 foot gravel inflow rates, and checking for steady-state. The Thomas algorithm subrouting solves the tridiagonal matrices generated but the row and column calculations. Data Print is a subroutine which prints the initial data and the results of the calculations at the final time step (if steady-state is not achieved), at steady-state, or at either of two arbitrarily chosen time steps. Appendix B is an example of the initial data format produced by Data Print. The Harmonic Mean function simplifies the program entries in the column and row calculation portion of the main program.

## MODEL CALIBRATION

In order to calibrate the model water levels of the Santa Monica and Southern California Water Company wells were measured under operating conditions on Monday, July 19, 1983. These conditions consisted of production from SoCal#8, SM12, SM15, and SM16 and injection in SM7 and SM9. At 10:00 am the injection wells were shut down and the water levels of all the wells in the basin were monitored weekly for six weeks (42 days). The aquifer thickness was assigned by averaging the data from well logs (stratigraphy) of all of the Santa Monica and Southern California Water wells. The aquifer thickness value of 200 feet was determined by deducting the depth non-producing strata from the total production depth of the active wells.

Inflow from the north and south was given the values assigned by Poland (1951) of 4 million gallons per day from the north and 2 million gallons per day from the south. The storage coefficient assigned to the aquifer (0.001569) was determined from non-equilibrium pumping tests conducted in 1982. Variation of the storage coefficient within reasonable limits for aquifer formations as found at Charnock (0.01 to 0.0001) had negligible effect on the model output. The hydraulic conductivity was varied and the value chosen such that the model output, when Dt equaled 1.0 days, gave the water level values which most closely approximated the observed water levels (Table 3). Dt was then varied from 3.8 days to 0.125 over the calibration period of 42 days. The model water level values from each Dt were plotted against the observed values and the average Dt of the intersections of the calculated water levels and the observed water levels was found to be 0.95 days (Figure 8). It must be noted that at Dt = 0.25 oscillations near the boundaries begin and increase as Dt is decreased. Table 4 compares the model calculated water levels based on the calibration values above with the observed water levels under conditions of production only (no injection).

Table 3

Measured and Calculated Water Levels

Dt = 1.0 K = 15.0

Water Level (feet)

| Well | Observed | Calculated | % Difference |
|---|---|---|---|
| SoCal #8 | 171 | 173 | +1.2 |
| SoCal #9 | 189 | 186 | -1.6 |
| SM 7 | 186 | 187 | +0.5 |
| SM 9 | 180 | 172 | -4.4 |
| SM 13 | 188 | 189 | +0.5 |
| SM 14 | 184 | 189 | +2.7 |
| SM 17 | 184 | 186 | +1.0 |

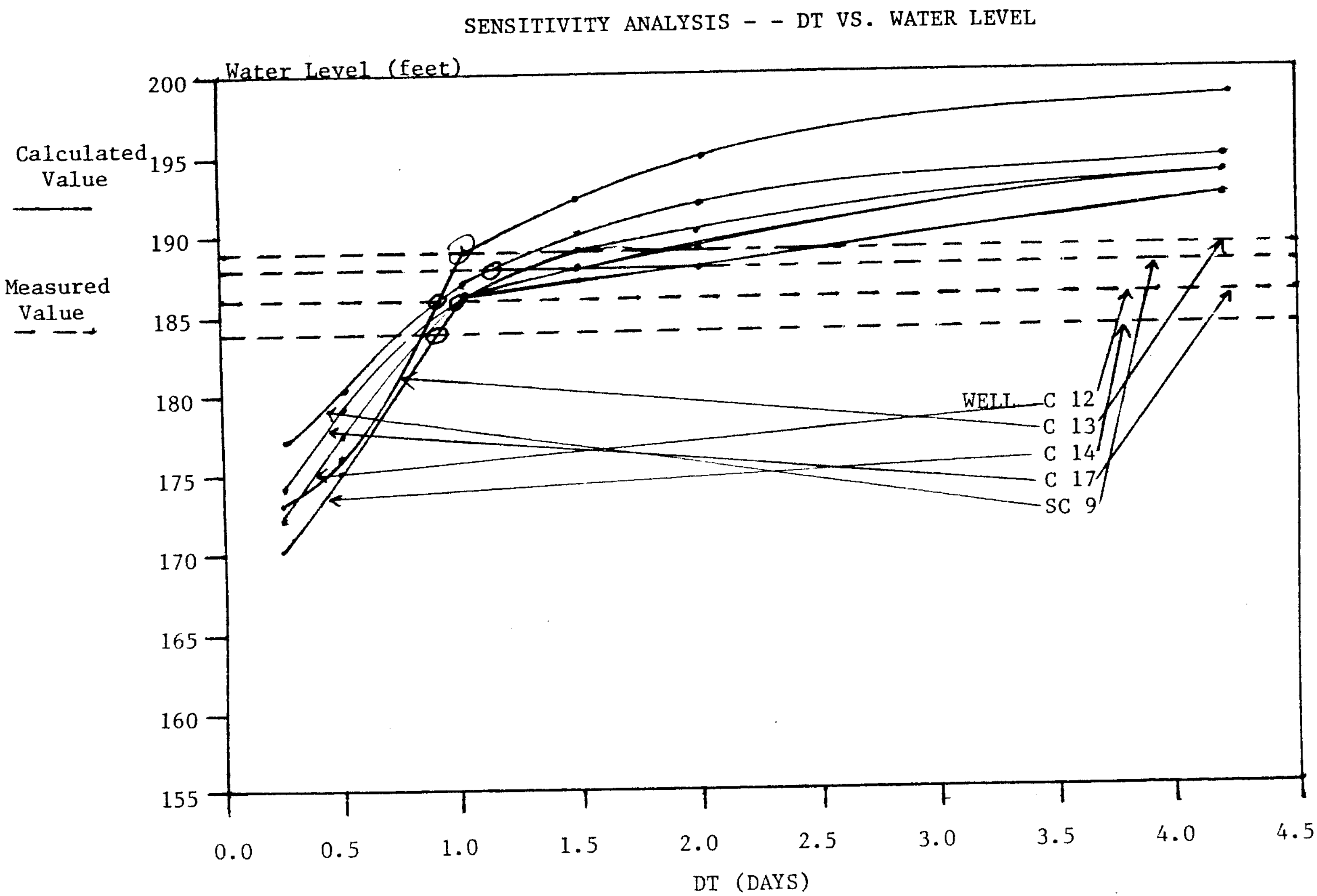


Fig. 8. SENSITIVITY ANALYSIS, DT VS. WATER LEVEL

Table 4

**Measured and Calculated Water Levels**

Dt = 0.95 K = 15.0

Water Level (feet)

| Well | Observed | Calculated | % Difference |
|---|---|---|---|
| SoCal #8 | 171 | 173 | +1.2 |
| SoCal #9 | 189 | 188 | -1.6 |
| SM 7 | 186 | 187 | +0.5 |
| SM 9 | 180 | 174 | -3.3 |
| SM 13 | 188 | 189 | +0.5 |
| SM 14 | 184 | 188 | +2.1 |
| SM 17 | 184 | 186 | +1.0 |

## MODEL VERIFICATION

Using the model parameters established during the calibration phase, injection at the Santa Monica wells 7 and 9 was simulated for a period of 45 days and the model calculated water levels compared with the observed water levels of July 19, 1983 (Table 5). The calculated values at the observable wells were all within 2 feet of the observed values (1% error). This was determined to be satisfactory verification based on the available data.

Table 5

Measured and Calculated Water Levels

Production and Injection

Dt = 0.95 K = 15.0

Water Levels (feet)

| Well | Observed | Calculated | % Difference |
|---|---|---|---|
| SoCal #19 | 189 | 187 | -1.1 |
| SM 13 | 196 | 147 | +0.5 |
| SM 14 | 200 | 201 | +0.5 |
| SM 17 | 191 | 189 | -1.0 |
| * | | | |

*Note that SoCal #8, SM7 and SM9 were not measurable under these conditions

## Historical Flow Simulation

In order to simulate the historical overdraft conditions of the 1930's the 10 current well sites were each assigned a production rate of 143,216. cubic feet per day, one tenth of the four year maximum historical production rate which appears to have produced the overdraft. The model was run for 350 time steps with DT = 1.90 days and each time step equal to 3.80 days. The model reported head distributions at 175 time steps (2 years) and at 350 time steps (4 years).

The results showed a water level pattern similar to that which existed in 1940 in the area near the current wells (80 to 100 feet below sea level). In the Ballona Gap, however, the model failed to generate the drawdown recorded in 1940. This failure is probably due to an inaccurate description of the aquifer parameters in the southerly or Ballona Gap portion of the study area. Unfortunately, there are no currently active water producers in this area and the historical records of production are inadequate for determining the aquifer parameters.

# CONCLUSIONS

The model appears to have the potential for prediction as shown by its ability to duplicate actual conditions in the area of current extraction activity. If more data can be obtained on the characteristics of the Ballona Gap area and the water levels in the adjoining sub-basins of the Ballona Gap (Crestal and Coastal basins) model verification may be extended to the entire study area. It is possible that the inflow data determined by Poland may be in error either as to volume of inflow, the source of the inflow or the distribution of the inflow. Additionally, the historic information related to the number and quantity of pumpers creating the historic drawdown levels may not be accurate. Significant quantities of water may be inflowing to the Charnock sub-basin from the crestal sub-basin in the area north of the Ballona Gap area at the present time due to the lack of production in that sub-basin while at the time of the severe overdrafts higher production in the crestal sub-basin lowered the water table sufficiently such that interbasin inflows were not occurring. It appears that research in the form of water level and aquifer exploration will be required to verify the assumptions regarding the aquifer parameters, boundary fault permeability and other assumptions based on historic data. Model verification for the entire study area will be required as a basis for modeling groundwater quality in the study area.

# APPENDIX A

## FORTRAN PROGRAM CODE

```
C...ALTERNATING DIRECTION IMPLICIT METHOD APPLIED TO THE MODELLING
C   OF THE SANTA MONICA, CHARNOCK AQUIFER.
C
C   PART OF THE MASTER OF SCIENCE REQUIREMENTS FOR ENGINEERING
C   DR. M.K.STENSTROM, ADVISOR
C
C   PROGRAMMER  JOHN E. HOAGLAND
C
C
      DIMENSION A(080),B(080),C(080),D(080),BETA(080),GAMA(080)
      DIMENSION Q(080,045),K(080,045),S(080,045),T(080,045)
      DIMENSION H(80),HPRE(80,45),HL(80,45,3),DX(45),DY(80),WLO(80,45)
      DIMENSION DWDNW(20),DWDNE(20),FFGW(20),FFGE(20),HS(80,45)
      DIMENSION PVAL (8,5,5),CVAL(7,5,5)
C
C
      INTEGER TSMAX,CN,RN,CNL,RNL,TRPT1,TRPT2,RNLL,CNLL,TS
      REAL K,KDF
C........ TSMAX = MAXIMUN NUMBER OF TIME STEPS ALLOWED
C         RN = # OF ROWS        CN = # OF COLUMNS
C         RNL = RN - 1          CNL = CN - 1
C         TRPT1 & TRPT2 = TIME STEPS AT WHICH THE INTERMEDIATE HEAD
C           LEVELS CAN BE PRINTED
C
C..........READ AND ASSIGN THE INTIAL PARAMETERS TO THE MODEL AREA.....
C         1 .
C
      TS-0
      M=0
1     READ(5,3)TSMAX,TRPT1,TRPT2,CN,RN,DT,DEBUGS
      IF(TSMAX.EQ.0)GO TO 500
      READ(5,4)QDF,KDF,SDF,QN,QS,ATHIK
3     FORMAT(513,F6.3,F4.1)
4     FORMAT(F8.6,F7.2,F8.6,2(F8.0),1X,F4.0)
      RNL=RN-1
      CNL=CN-1
      RNLL=RN-2
      CNLL=CN-2
      READ(5,6) (DX(J),J=1,CN)
6     FORMAT(14(F5.1))
      READ(5,6) (DY(I),I=1,RN)
      READ(5,2) (FFGW(I),I=1,18)
2     FORMAT(14(F5.1))
      READ(5,2) (FFGE(I),I=1,20)
      DO 9 I=1,RN
      DO 9 J=1,CN
      Q(I,J)=QDF*DY(I)*DX(J)
      K(I,J)=KDF
      S(I,J)=SDF
      HL(I,J,1)=ATHIK
      HS(I,J)=ATHIK
9     WLO(I,J)=ATHIK
```

```
      DO 10 J=2,CNL
      Q(2,J)=Q(1,J)-((DX(J)/6600.)*QN)/7.48
10    Q(RNL,J)=Q(RN,J)-((DX(J)/6600.)*QS)/7.48
      DO 11 I=1,RN
      DO 11 J=1,CN
      K(I,1)=0.0
      K(I,CN)=0.0
      K(1,J)=0.0
11    K(RN,J)=0.0
      READ(5.15)NW
15    FORMAT(13)
C
C
C......OUTPUT HEADING......
C
C
      WRITE(6,17)
17    FORMAT('1','TWO DIMENSIONAL MODEL OF THE CHARNOCK SUB-BASIN')
      WRITE (6,18)
18    FORMAT('0','MODEL AREA DIMENSIONS ARE 17600 FT BY 6600 FT AND DX,
     1DY ARE VARIABLE')
      DT2=2.*DT
      WRITE(6,19)DT2
19    FORMAT('0','EACH TIME STEP IS ',F8.4,' DAYS.')
      WRITE(6,20)NW
20    FORMAT('0','THERE ARE',13,' WELLS IN THE MODEL LOCATED:')
      DO 30 IDX=1,NW
      READ(5,22)I,J,QW
22    FORMAT(213,F9.1)
      IF(QW)24,25,26
24    Q(I,J)=Q(I,J)+QW
      WRITE(6,27)QW,I,J
27    FORMAT('0','A ',F9.1,' CFD RECHARGE WELL IN BLOCK ',I3,' , ',I3)
      L=IDX
      GO TO 30
25    WRITE(6,28)I,J
28    FORMAT('0','AN INACTIVE WELL IN BLOCK ',I3,', ',I3)
      L=IDX
      GO TO 30
26    Q(I,J)=Q(I,J)+QW
      WRITE(6,29)QW,I,J
29    FORMAT('0','A ',F9.1,' CFD PRODUCTION WELL IN BLOCK ',13,' , ',13
     1)
      L=IDX
30    CONTINUE
      L=0
      WRITE(6,31)ATHIK
31    FORMAT('0','THE INITIAL SATURATED THICKNESS OF THE AQUIFER IS ',
     1F4.0,' FEET.')
      WRITE(6,32)KDF,SDF
32    FORMAT('0','DEFAULT HYDRAULIC CONDUCTIVITY = ',F8.3,5X,'DEFAULT
     1ST ORAGE FACTOR = ',F8.6)
```

```
      WRITE(6,33)QS,QN
33    FORMAT('0','SOUTHERN BOUNDARY INFLOW = ',F8.0,' GPD',5X,'
     1NORTHERN BOUNDARY INFLOW = ',F8.0,' GPD')
      FLOWE=0.0
      FLOWW=0.0
      CALL DATPRT(M,HL,TSMAX,TRPT1,TRPT2,RN,CN,FLOWE,FLOWW,DEBUGS)
C
C
44    TS=TS+1
36    IAC=0
37    IAC=IAC+1
      IF(IAC.EQ.8)GO TO 404
      BB=0.0
C
C...........START ADI.................
C
C
C.....CALCULATE TRANSMISSIVITIES VALUES FOR THIS TIME STEP.....
C
C
      DO 34 I=1,RN
      DO 34 J=1,CN
34    T(I,J)=HL(I,J,1)*K(I,J)
C
C
      IF(DEBUGS)42,42,40
C
C.............COLUMN CALCULATIONS......................
C
42    L=2
      DO 100 I=2,RNL
      B(2)=-HR(T(I,2),T(I,1),DX(2),DX(1))/DX(2)-HR(T(I,2),T((I+1),2),DY
     1(I),DY(I+1))/DY(I)-HR(T(I,2),T((I-1),2),DY(I),DY(I-1))/DY(I)-S(I,
     12)/DT-HR(T(I,2),T(I,3),DX(2),DX(3))/DX(2)
      C(2)=HR(T(I,2),T(I,3),DX(2),DX(3))/DX(2)
      D(2)=Q(I,2)/(DX(2)*DY(I))-HL(I,2,1)*S(I,2)/DT-HL((I-1),2,1)*HR(T(
     1I,2),T((I-1),2),DY(I),DY(I-1))/DY(I)-HL((I+1),2,1)*HR(T(I,2),T((I
     1+1),2),DY(I),DY(I+1))/DY(I)-HR(T(I,2),T(I,1),DX(2),DX(1))/DX(2)
      DO 95 J=3,CNLL
      A(J)=HR(T(I,J),T(I,(J-1)),DX(J),DX(J-1))/DX(J)
      B(J)=-HR(T(I,J),T(I,(J+1)),DX(J),DX(J+1))/DX(J)-HR(T(I,J),T(I,(J-
     11)),DX(J),DX(J-1))/DX(J)-HR(T(I,J),T((I-1),J),DY(I),DY(I-1))/DY(I
     1)-HR(T(I,J),T((I+1),J),DY(I),DY(I+1))/DY(I)-S(I,J)/DT
      C(J)=HR(T(I,J),T(I,(J+1)),DX(J),DX(J+1))/DX(J)
      D(J)=Q(I,J)/(DX(J)*DY(I))-HL(I,J,1)*S(I,J)/DT-HL((I-1),J,1)*HR(T(
     1I,J),T((I-1),J),DY(I),DY(I-1))/DY(I)-HL((I+1),J,1)*HR(T(I,J),T((I
     1+1),J),DY(I),DY(I+1))/DY(I)
95    CONTINUE
      A(CNL)=HR(T(I,CNL),T(I,CNLL),DX(CNL),DX(CNLL))/DX(CNL)
      B(CNL)=-HR(T(I,CNL),T(I,CNLL),DX(CNL),DX(CNLL))/DX(CNL)-HR(T(I,CN
     1L),T((I+1),CNL),DY(I),DY(I+1))/DY(I)-HR(T(I,CNL),T((I-1),CNL),DY(
```

```
     1I),DY(I-1))/DY(I)-S(I,CNL)/DT-HR(T(I,CNL),T(I,CN),DX(CNL),DX(CN))
     1/DX(CNL)
      D(CNL)=Q(I,CNL)/DX(CNL)*DY(I))-HL(I,CNL,1)*S(I,CNL)/DT-HL((I-1),
     1CNL,1)*HR(T(I,CNL),T((I-1),CNL),DY(I),DY(I-1))/DY(I)-HL((I+1),CN
     1L,1)*HR(T(I,CNL),T((I+1),CNL),DY(I),DY(I+1))/DY(I)-HR(T(I,CNL),T
     1(I,CN),DX(CNL),DX(CN))/DX(CNL)
      CALL TA(A,B,C,D,H,CNL,L)
      DO 96 J=1,CNLL
96    HS(I,(J+1))=H(J)
100   CONTINUE
      IF(DEBUGS)130,130,103
130   DO 131 I=1,RN
      DO 131 J=1,CN
131   HL(I,J,2)=HS(I,J)
C
C
C
C...............ROW CALCULATIONS......................
C
C
      L=2
      DO 200 J=2,CNL
      B(2)=-HR(T(2,J),T(3,J),DY(2),DY(3))/DY(2)-HR(T(2,J),T(2,(J-1)),D
     1X(J),DX(J-1))/DX(J)-HR(T(2,J),T(2,(J+1)),DX(J),DX(J+1))/DX(J)-S(
     12,0)/DT-HR(T(2,J),T(1,J),DX(2),DX(1))/DX(2)
      C(2)=HR(T(2,J),T(3,J),DY(2),DY(3))/DY(2)
      D(2)=Q(2,J)/(DX(J)*DY(2))-HL(2,J,1)*S(2,J)/DT-HL(2,(J+1),1)*HR(T
     1(2,J),T(2,(J+1)),DX(J),DX(J+1))/DX(J)-HL(2,(J-1),1)*HR(T(2,J),T(
     12,(J-1)),DX(J),DX(J-1))/DX(J)-HR(T(2,J),T(1,J),DY(2),DY(1))/DY(2
     11)
      DO 160 I=3,RNLL
      A(I)=HR(T(I,J),T((I-1),J),DY(I),DY(I-1))/DY(1)
      B(I)=-HR(T(I,J),T(I,(J+1)),DX(J),DX(J+1))/DX(J)-HR(T(I,J),T(I,(J
     1-1)),DX(J),DX(J-1))/DX(J)-HR(T(I,J),T((I-1),J),DY(I),DY(I-1))/DY
     1(I)-HR(T(I,J),T((I+1),J),DY(I),DY(I+1))/DY(I)-S(I,J)/DT
      C(I)=HR(T(I,J),T((I+1),J),DY(I),DY(I+1))/DY(I)
      D(I)=Q(I,J)/(DX(J)*DY(I))-HL(I,J,1)*S(I,J)/DT-HL(I,(J+1),1)*HR(T
     1(I,J),T(I,(J+1)),DX(J),DX(J+1))/DX(J)-HL(I,(J-1),1)*HR(T(I,J),T(
     1I,(J-1)),DX(J),DX(J-1))/DX(J)
160   CONTINUE
      A(RNL)=HR(T(RNL,J),T(RNLL,J),DY(RNL),DY(RNLL))/DY(RNL)
      B(RNL)=-HR(T(RNL,J),T(RNLL,J),DY(RNL),DY(RNLL))/DY(RNL)-HR(T(RNL
     1,J),T(RNL,(J+1)),DX(J),DX(J+1))/DX(J)-HR(T(RNL,J),T(RNL,(J-1)),D
     1X(J),DX(J-1))/DX(J)-S(RNL,J)/DT-HR(T(RNL,J),T(RN,J),DY(RNL),DY(R
     1N))/DY(RN)
      D(RNL)=Q(RNL,J)/(DX(J)*DY(RNL))-HL(RNL,J,1)*S(RNL,J)/DT-HL(RNL,(
     1J+1),1)*HR(T(RNL,J),T(RNL,(J+1)),DX(J),DX(J+1))/DX(J)-HL(RNL,(J-
     11),1)*HR(T(RNL,J),T(RNL,(J-1)),DX(J),DX(J-1))/DX(J)-HR(T(RNL,J),
     1T(RN,J),DY(RNL),DY(RN))/DY(RNL)
      CALL TA(A,B,C,D,H,RNL,L)
      DO 165 I=1,RNLL
```

```
165    HS((I+1),J)=H(I)
200    CONTINUE
230    DO 225 I=1,RN
       DO 225 J=1,CN
225    HL(I,J,3)=HS(I,J)
C
C....CHECK THE EAST AND WEST BOUNDARIES FOR 50 FOOT GRAVEL INFLOW...
C
C....DETERMINE THE DRAWDOWN IN THE AREAS OF POTENTIAL FLOW....
C
       DO 260 I=1,18
260    DWDNW(I)=WLO((57+I),2)-HL((57+I),2,3)
       DO 261 I=1,14
261    DWDNE(I)=WLO((41+I),CNL)-HL((41+I),CNL,3)
       SUMW=0.0
       SUME=0.0
       FLOWE=0.0
       FLOWW=0.0
       DO 262 I=1,18
262    SUMW=SUMW+DWDNW(I)
       DO 263 I-1,14
263    SUME=SUME+DWDNE(I)
       IF(SUME.LT.2.0)GO TO 265
       DO 264 I=1,14
       Q((41+I),CNL)=Q((41+I),CNL)+(-K((41+I),CNL)*FFGE(I)*DY(41+I)*DWD
      1NE(I))/DX(CN)
264    FLOWE=FLOWE+Q((41+I),CNL)
       BB=1.0
265    IF(SUMW.LT.2.0)GO TO 232
       DO 266 I=1,18
       Q((57+I),2)=Q((57+I),2)+(-K((57+I),2)*FFGW(I)*DY(57+I)*DWDNW(I))
      1/DX(1)
266    FLOWW=FLOWW+Q((57-I),2)
       GO TO 37
232    IF(BB.EQ.1.0)GO TO 37
       M=M+1
       CALL DATPRT(M,HL,TSMAX,TRPT1,TRPT2,RN,CN,FLOWE,FLOWW,DEBUGS)
       IF(M.EQ.TSMAX)GO TO 500
       IF(TS.EQ.TSMAX)GO TO 500
       TOT1=0.0
234    DO 235 I=2,RNL
       DO 235 J=2,CNL
235    TOT1=TOT1+(HL(I,J,1)-HL(I,J,3))
       IF(ABS(TOT1).LT.1.0)GO TO 410
       DO 240 I=1,RN
       DO 240 J=1,CN
240    HL(I,J,1)=HL(I,J,3)
       WRITE(6,250)M,TS
250    FORMAT('0','M = ',I4,'  TIME STEP = ',I4)
       GO TO 44
400    WRITE(6,402)
```

```
      GO TO 480
401   WRITE(6,403)
      GO TO 480
402   FORMAT('0','TOO MANY ITERATIONS IN THE COLUMN CALCULATIONS')
403   FORMAT('0','TOO MANY ITERATIONS IN THE ROW CALCULATIONS')
404   WRITE(6,405)
405   FORMAT('0','EAST/WEST FLOWS, TOO MANY ITERATIONS')
410   WRITE(6,411)
411   FORMAT('0','**********STEADY-STATE ACHIEVED**********')
480   M=TSMAX
      CALL DATPRT(M,HL,TSMAX,TRPT1,TRPT2,RN,CN,FLOWE,FLOWW,DEBUGS)
      IF(DEBUGS)500,500,490
490   DO 494 I=1,7
      DO 494 J=1,5
      DO 494 IJ=1,5
494   CONTINUE
500   WRITE(6,501)
501   FORMAT('0','........THATS ALL FOLKS........')
      STOP
      END
C
C
C.....................THOMAS ALGORITHUM...........................
C
C
      SUBROUTINE TA(A,B,C,D,H,N,L)
      DIMENSION A(080),B(080),C(080)D(080),BETA(080),GAMA(080)
      DIMENSION H(080)
      N1=N-1
      N2=N-2
      BETA(L)=B(L)
      GAMA(L)=D(L)/B(L)
      INX=L+1
      DO 700 I=INX,N
      BETA(I)=B(I)-A(I)*C(I-1)/BETA(I-1)
700   GAMA(I)=(D(I)-A(I)*GAMA(I-1))/BETA(I)
      H(N1)=GAMA(N)
      DO 710 I=1,N2
710   H(N1-I)=GAMA(N-1)-C(N-I)*H(N1-(I-1))/BETA(N-I)
      RETURN
      END
C
C
C...................DATA PRINT...................
C
C
      SUBROUTINE DATPRT(M,HL,TSMAX,TRPT1,TRPT2,RN,CN,FLOWE,FLOWW,DEBUG
     1S)
      DIMENSION HL(080,045,3)
      INTEGER RN,CN,TSMAX,TRPT1,TRPT2
      IF(DEBUGS)680,605,650
605   IF(M.EQ.0)GO TO 610
```

```
      IF(M.EQ.TRPT1.OR.M.EQ.TRPT2)GO TO 620
      IF(M.EQ.TSMAX)GO TO 630
      GO TO 640
610   IK=1
      WRITE(6,611)
611   FORMAT('1','THE INITIAL CONDITIONS ARE:')
615   DO 619 I=1,RN
      WRITE(6,616)I
616   FORMAT(' ','ROW = ',I3)
      WRITE(6,617) (HL(I,J,IK),J=1,CN)
617   FORMAT(' ',20(1X,F4.0.1X))
619   CONTINUE
      GO TO 640
620   IK=3
      WRITE(6,621)M
621   FORMAT('1','THE SIMULATION AFTER ',I3,' TIME STEPS IS:')
      WRITE(6,622)FLOWE,FLOWW
622   FORMAT('0','EAST FFG FLOW = ',F8.6,' WEST FGG FLOW = ',F8.6)
      GO TO 615
630   IK=3
      WRITE(6,631)
631   FORMAT('1','THE FINAL HEAD DISTRIBUTION FOR THE SIMULATION IS:')
      WRITE(6,632)FLOWE,FLOWW
632   FORMAT('0','EAST FFG FLOW = ',F8.6,' WEST FFG FLOW = ',F8.6)
      GO TO 615
650   IF(M.EQ.0)GO TO 660
      IF(M.EQ.TSMAX)GO TO 670
      GO TO 640
660   WRITE(6,661)
661   FORMAT('1','THE INTIAL CONDITIONS ARE:')
      IK=1
665   DO 668 I=1,71,10
      WRITE(6,666)I
666   FORMAT(' ','ROW = ',I3)
      WRITE(6,667) (HL(I,J,IK),J=1,37,4)
667   FORMAT(' ',10(1X,F4.0,1X))
668   CONTINUE
      GO TO 640
670   IK=3
      WRITE(6,671)
671   FORMAT('1','THE FINAL HEAD DISTRIBUTION IS:')
      GO TO 665
680   DO 690 I=20,35
      WRITE(6,682)I
682   FORMAT(' ','ROW = ',I3)
      WRITE(6,684) (HL(I,J,3),J=6,22)
684   FORMAT(' ',17(1X,F4.0,1X))
690   CONTINUE
      GO TO 640
640   RETURN
      END
```

```
C
C
C...................HARMONICA MEAN FUNCTION...........................
C
C
      FUNCTION HR(TO,TT,SO,ST)
      HR=2.*TO*TT/((TO*ST)+(TT*SO))
      RETURN
      END
```

# APPENDIX B

## MODEL PARAMETER SUMMARY

TWO DIMENSIONAL MODEL OF THE CHARNOCK SUB-BASIN

MODEL AREA DIMENSIONS ARE 17600 FT BY 6600 FT AND DX, DY ARE VARIABLE

EACH TIME STEP IS 1.0000 DAYS.

THERE ARE 10 WELLS IN THE MODEL LOCATED:

AN INACTIVE WELL IN BLOCK 32 , 8

A 144385.0 CFD PRODUCTION WELL IN BLOCK 32 , 9

AN INACTIVE WELL IN BLOCK 25 , 20

AN INACTIVE WELL IN BLOCK 27 , 15

A 95775.0 CFD PRODUCTION WELL IN BLOCK 23 , 17

AN INACTIVE WELL IN BLOCK 27 , 18

A 164214.0 CFD PRODUCTION WELL IN BLOCK 26 , 13

A 433155.0 CFD PRODUCTION WELL IN BLOCK 23 , 20

AN INACTIVE WELL IN BLOCK 25 , 12

AN INACTIVE WELL IN BLOCK 27 , 16

THE INITIAL SATURATED THICKNESS OF THE AQUIFER IS 200. FEET.

DEFAULT HYDRAULIC CONDUCTIVITY = 15.000 DEFAULT STORAGE FACTOR = 0.001569

SOUTHERN BOUNDARY INFLOW = 2000000. GPD NORTHERN BOUNDARY INFLOW = 4000000.

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