2-4 DIGITAL COMPUTER TECHNIQUES FOR GLOW PROBLEMS

There are four broad classes of groundwater models which are (1) physical, (2) analog, (3) analytycal formula, (4) numerical, which include the finite difference and the finite element. The first two models are not presently favored. Analytical formulas are widely used for flow problems. They require only paper, pencil, and tables of well function, due to idealized aquifer and boundary conditions. With the aid of a pocket-computer, they can be applied to wide areas.

In more compex hydrogeological conditions, numerical models must be used to avoid inaccuracy. There are many numerical techniques which include the finite difference (FD) and the finite element (FE). They only differ from one another in the way the differential equations are approximated and solved with a digital computer. Comparision between the FD and the FE is shown in Table 2-1. Each technique has its advantages and disadvantages.

2-4-1 FINITE DIFFERENCE METHOD

(1) Governing Equation

The partial differential equation which governs the non-steady state two-dimensional flow of groundwater in an artesian nonhomogeneous and isotropic aquifer, can be stated as follows :

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W \quad \cdots\cdots\cdots\cdots \quad (21)$$

where,

T : transmissivity (L^2T^{-1})

S : storativity (dimensionless)

h : artesian head (L)

x,y: cartesian coordinates (L)

w : source or sink (L T^{-1})

t : time (T)

Table 2-1 Comparsion between FD and FE

Attribute	FD	FE
1 Code Availability	Excellent	> Good
2 Convenience	Mesh generation relatively automatic data handling can be easy	> by hand or automatic
3 Accuracy	Mesh design roughly approximates boundary and location of well	< Mesh can follow boundary condition, observation well, and pumping well
4 Flexibility	Easier to modify	> not easy
5 Code Efficency	Usually in-core	≷ in-core or out-core

(2) Finite Difference Approximation

In the finite difference technique, space and time variables are treated as discrete parameters. Firstly, the aquifer investigated is subdivided into rectangular blocks by the grid system. These blocks have volume $\Delta x \ \Delta ym$ where "m" is the thickness of the aquifer. (Figure 2-8)

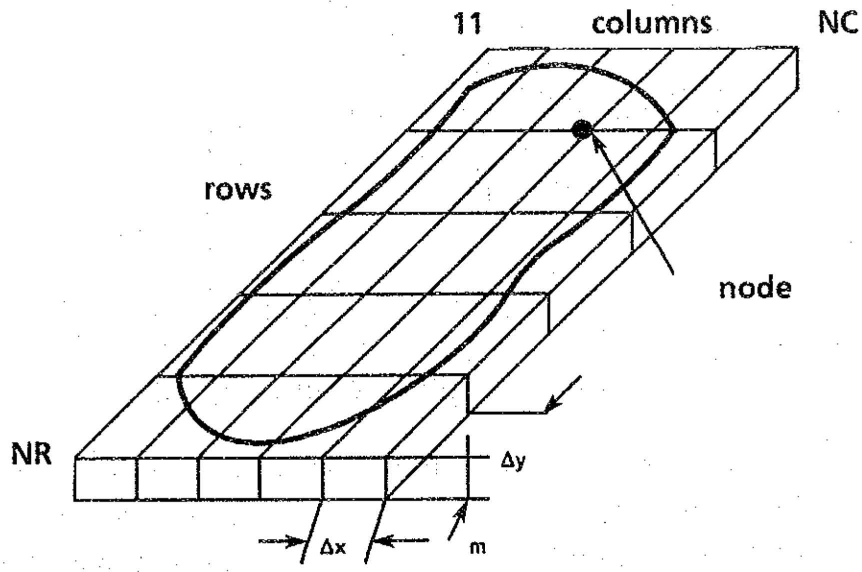


Figure 2-8 Grid System

The differentials ∂x and ∂y are approximated by the finite lengths Δx and Δy, respectively. The area Δx and Δy should be small compared with the total area of the aquifer, so that the discrete model reasonable represents the continuous aquifer.

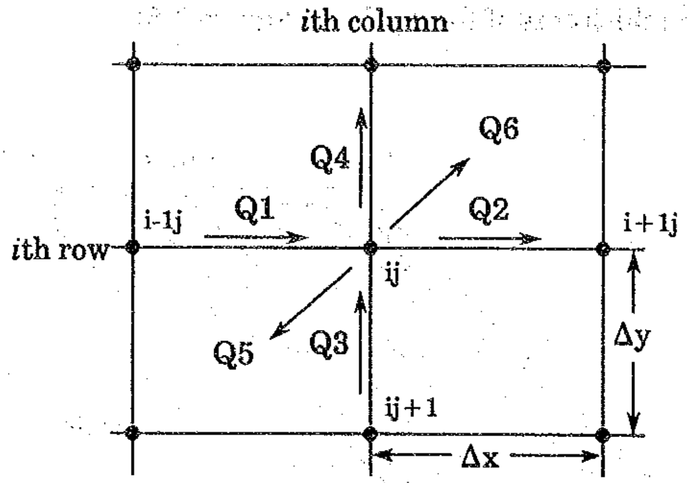


Figure 2-9 Finite Difference Grid

The groundwater flow in the aquifer is approximated by the flow between nodes. Flow rate terms Q1, Q2, Q3, . . . Q6 are arbitrarily assigned flow directions as illustrated in Figure 2-9. Q1, Q2, Q3 and Q4 represent node-to-node water transfer rates. Q5 is the flow rate associated with the amount of water taken into or released from storage per unit time increment Δt. Q6 is defined as a net withdrawal rate and represents source or sink term W of Eq. (11). The conservation of mass requires that the flow rates entering and leaving the node ij are equal as follows :

$$Q1 + Q3 = Q2 + Q4 + Q5 + Q6 \qquad (22)$$

Determining the values of the flow rate terms of Eq. (22) involves three considerations. First, it is necessary to define what portion of the aquifer is represented by each individual term. Secondly, it must be kept in mind that, although the flow rates may take place in any direction in the aquifer system, they are restricted to the x and y directions in the finite difference approach. The portions of the aquifer included in the flow rate terms then may be referred to as 'vector volumes' to emphasize that not only a volume but also the direction of flow is being considered. Finally, since time is discretized, Eq. (22) represents an instantaneous balance at the end of a time increment.

(3) Derivation of Approximate Equation

Horizontal projections of the vector volume of the node-to-node flow rate terms, Q1, Q2, Q3 and Q4, are defined as illustrated in Figure-11. All Vector volumes of Figure-12 have a vertical dimension extending the full depth of the aquifer, m. Furthermore, the portion of aquifer involved with each of these flow rate terms extends in width one-half of the grid interval of either side of the line between node points, and is equal in length to the grid interval. Darcy's Law is then applied to the flow rate terms, Q1 through Q4, to give

$$Q1 = T_{i-1,j,2}(h_{i-1,j} - h_{i,j})\,\Delta y/\Delta x \tag{23a}$$

$$Q2 = T_{i,j,2}(h_{i,j} - h_{i+1,j})\,\Delta y/\Delta x \tag{23b}$$

$$Q3 = T_{i,j,1}(h_{i,j+1} - h_{i,j})\,\Delta x/\Delta y \tag{23c}$$

$$Q4 = T_{i,j-1,1}(h_{i,j} - h_{i,j-1})\,\Delta x/\Delta y \tag{23d}$$

where, $T_{i,j,1}$: aquifer transmissivity within the vector volume between nodes i, j, and i, j+1 (see Figures 2-10c and d)

$T_{i,j,2}$: aquifer transmissivity within the vector volume between nodes i, j, and i+1, j (see Figure 2-10a and b)

$h_{i,j}$: calculated heads at the end of a time increment measured from an arbitrary reference level at node i, j

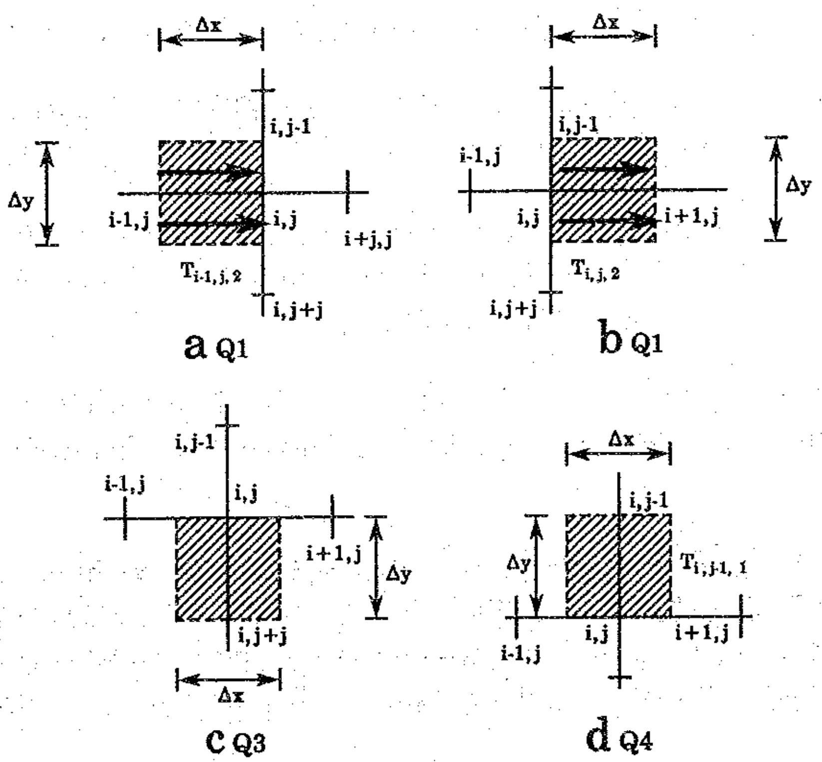


Figure 2-10 Vector Volumes for Node-to-Node Flow Rate Terms

Horizontal projections of the vector volumes of the flow terms Q5 and Q6, extend the full depth of the aquifer and have horizontal dimensions of Δx and Δy, the volumes being centered around the node point i, j.

The flow rate terms Q5, representing the rate at which water is taken into storage, is given by

$$Q5 = S\,\Delta x\,\Delta y\,(h_{i,j}\;h0_{i,j})\,/\,\Delta t \qquad (24)$$

where, $h0_{i,j}$: calculated head at node i, j at the end of the previous time increment Δt

Δt : time increment elapsed since last calculation of heads

The flow rate term Q6 is made equal to a net withdrawal rate from the vector volume of node i, j of Figure-11 as follows,

$$Q6 = Q1, j \qquad (25)$$

Substitution of Equations (23), (24) and (25) into Equation (22) results in

$$T_{i-1,j,2}(h_{i-1,j} - h_{i,j})\,\Delta y/\,\Delta x + T_{i,j,1}(h_{i,j+1} - h_{i,j})\,\Delta x\,/\,\Delta y = T_{i,j,2}\,(h_{i,j} - h_{i+1,j})\,\Delta y/\Delta x + T_{i,j-1,1}\,(h_{i,j} - h_{i,j-1})\,\Delta x\,/\,\Delta y\; + S\,\Delta x\Delta y\,(h_{i,j} - h0_{i,j})\,/\,\Delta t + Q_{i,j}$$

Dividing both sides of Equation (26) by the product of $\Delta x\,\Delta y$, yields

$$T_{i-1,j,2}\,(h_{i-1,j} - h_{i,j})\,/\,\Delta x^2 + T_{i,j,2}\,(h_{i+1,j} - h_{i,j})\,/\,\Delta x^2 + T_{i,j,1}(h_{i,j+1} - h_{i,j})\,/\,\Delta y^2 + T_{i,j-1,1}\,(h_{i,j-1} - h_{i,j})\,/\,\Delta y^2 = S\,(h_{i,j} - h0_{i,j})\,/\,\Delta t + Q_{i,j}\,/\,\Delta x\Delta y \qquad (27)$$

Equation (27) is the finite difference form of the partial differential equation (see Equation (21)) governing the nonsteady state, two-dimensional flow of groundwater in an artesian, nonhomogeneous aquifer.

Since an equation of the same form as Equation (27), is constructed for every node, a set of simultaneous equations should be solved for the principle unknown $h_{i,j}$.

The way of deriving the finite difference equation shown here, is based on physical standpoint involving Darcy's Law and the Principle of Conservation of Mass, which was given by Prickett and Lonnquist (1971). Remson et al. (1971) give rather complete mathematical derivations of finite difference equations.

2-4-2 FINITE ELEMENT METHOD

(1) Governing Equation

The governing differential equation for two-dimensional, essentially horizontal groundwater flow in a non-homogeneous, isotropic, aquifer with leakage is (see Figure 2-11)

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)+Q+\frac{k'}{b'}(H-h)=S\frac{\partial h}{\partial t} \qquad (28\text{-a})$$

where

T	:	transmissivity (L/T)
S	:	strativity (1)
h	:	artesian heads : solution variables (L)
x,y	:	Cartesian coordinates (L)
Q	:	net flux into the aquifer from point or distributed sources (and skins) (L/T)
k'	:	vertical permeability of the aquitard above the aquifer (L/T)
b'	:	thickness of the aquitard
H	:	piezometric head in a vertically ajacent aquifer separated by the aquitard (L)
t	:	time (T)

and boundary conditions are (see Figure 2-12)

$$\frac{\partial h}{\partial x}=V \qquad \text{on } C1 \qquad (28\text{-b})$$

$$h=HC \qquad \text{on } C2 \qquad (28\text{-c})$$

in which

V	:	flux into aquifer from uncomputed area
Hc	:	constant head
n	:	outward normal vector to the boundary

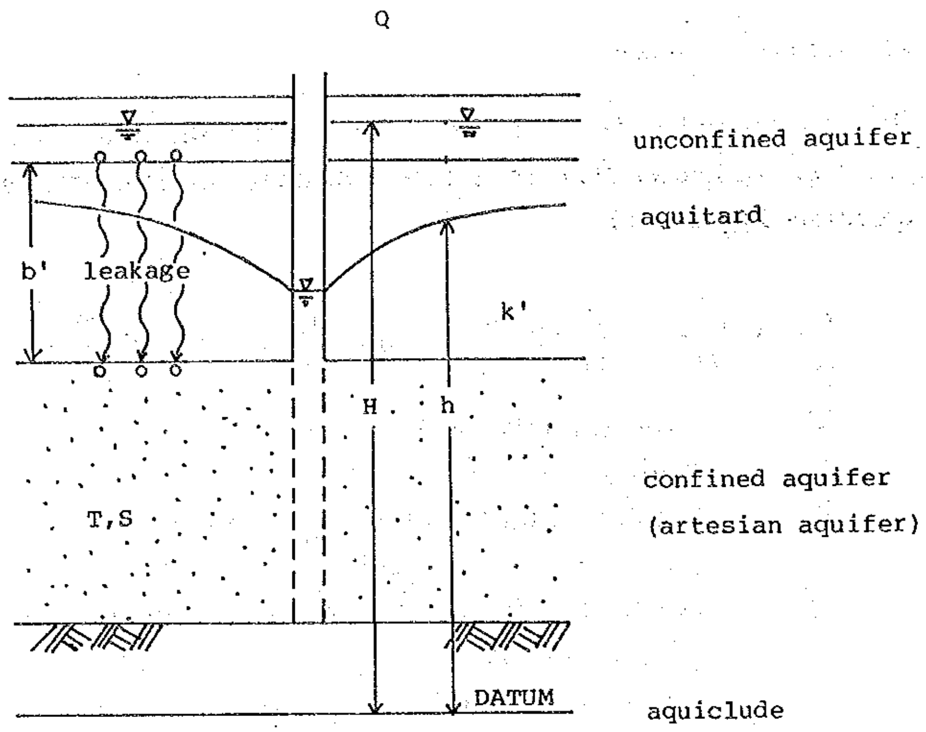


Fig. 2-11 Definition Sketch

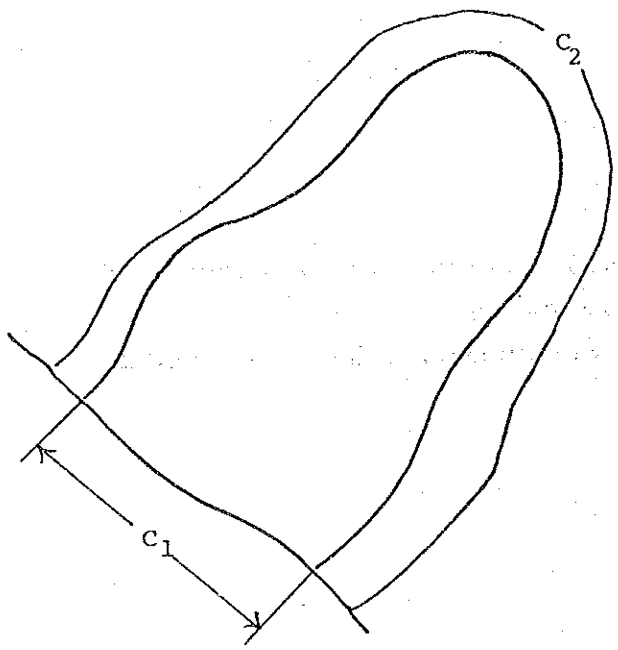


Fig. 2-12 Boundary Definitions

(2) Finite Element Formulation

Equation (28-a) is solved by dividing the aquifer domain into elements and points as illustrated in Figure 2-12.
In the divided triangular finite element the unknown artesian head can be approximated by the combination of linear shape function Ni (x,y) as

$$h = N_1 h_1 + N_2 H_2 + N_3 h_3 \qquad (29)$$

$$\left.\begin{aligned} N_1 &= \frac{a_1 + b_1 x + c_1 y}{2} \\ N_2 &= \frac{a_2 + b_2 x + c_2 y}{2} \\ N_3 &= \frac{a_3 + b_3 x + c_3 y}{2} \end{aligned}\right\} \qquad (30)$$

$a_1 = x_2 y_3 - x_3 y_2$

$a_2 = x_3 y_1 - x_1 y_3$

$a_3 = x_1 y_2 - x_2 y_1$

$b_1 = y_1 - y_3$

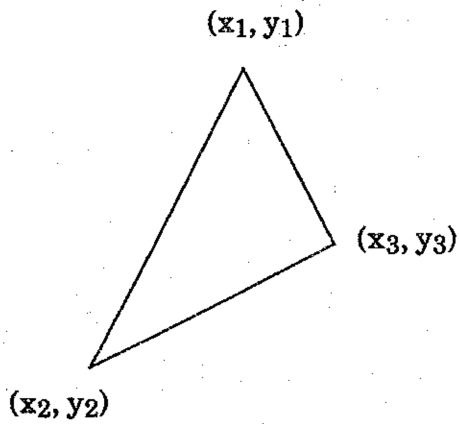
$b_2 = y_3 - y_1$

$b_3 = y_1 - y_2$

$c_1 = X_3 - X_2$

$c_2 = X_1 - X_3$

$c_3 = X_2 - X_1$



where h : unknown artesian heads in a triangular finite element

h_1, h_2, h_3 : artesian heads at each corner of a triangular finite element

Δ : area of a triangular finite element

x_i, y_i : cartesian coordinates at each corner of a triangular finite element $(i = 1, 2, 3)$

According to the Galerkin Method, the weighted and integrated equation residual is equal to zero. Therefore, Equation (28-a) is rearranged as follows :

$$\iint [N]^T [Te \frac{\partial [N]}{\partial x} \{he\} + Te \frac{\partial [N]}{\partial y} \{he\} + Qe + \frac{k'}{b'} [N]\{He\} - \frac{k'}{b'} [N]\{he\} - Se \frac{\partial [N]}{\partial t} \{he\}]\, d\Omega e = 0 \qquad (31)$$

In which superscript(e) denotes the particular element under consideration.

$$[N] = [N_1 \; N_2 \; N_3]$$

$$[N]^T = \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

$$\{h\} = \begin{Bmatrix} h_1 \\ h_2 \\ h_3 \end{Bmatrix}$$

Using Green's First Theorem and applying the boundary conditions (28-b) and (28-c), we have

$$\iint [Te \frac{\partial [N]^T}{\partial x} \frac{\partial [N]}{\partial x} + Te \frac{\partial [N]^{T'}}{\partial y} \frac{\partial [N]}{\partial y} + \frac{ke}{be} [N]^T [N] + \frac{ke'}{be'} [N]^T [N] + \frac{Se}{\Delta t} [N]^T [N] \; \{he\}]\, d\Omega e = \iint [N]^T Qe\, d\Omega e + \iint \frac{ke'}{be'} [N]^T [N] \{He\}\, d\Omega e + \iint \frac{Se}{\Delta t} [h]^T [N]\, d\Omega e \qquad (32)$$

Therefore, Equation (32) is rearranged as follows :

$$[Ke]\{he\} = \{fe\} \qquad (33)$$

in which

$$[Ke] = Te \iint \frac{\partial [N]^T}{\partial x} \frac{\partial [N]}{\partial x} d\Omega e + Te \iint \frac{\partial [N]^T}{\partial y} \frac{\partial [N]}{\partial y} d\Omega e + \frac{ke'}{be'} + \frac{ke'}{be'} \iint [N]^T [N]\, d\Omega e \qquad (34)$$

$$\{fe\} = -\iint [N]^T Qe\, d\Omega e + \iint \frac{ke'}{be'} [N]^T [N] d\Omega e \iint \frac{Se}{\Delta t} [N]^T [N] \{hoe\} d\Omega e \qquad (35)$$

where [ke] : element "stiffness" matrix

{fe} : element "force" vector

We can calculate according to the equation derived so far.

$$\iint Te \frac{\partial[N]^T}{\partial x} \frac{\partial[h]}{\partial x} \, d\Omega e$$

$$= Te \cdot \begin{pmatrix} \frac{\partial N_1}{\partial x} \\ \frac{\partial N_2}{\partial x} \\ \frac{\partial N_3}{\partial x} \end{pmatrix} \begin{pmatrix} \frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial x} & \frac{\partial N_3}{\partial x} \end{pmatrix} \cdot \Delta$$

$$= Te \cdot \begin{pmatrix} \frac{b_1}{2\Delta} \\ \frac{b_2}{2\Delta} \\ \frac{b_3}{2\Delta} \end{pmatrix} \begin{pmatrix} \frac{b_1}{2\Delta} & \frac{b_2}{2\Delta} & \frac{b_3}{2\Delta} \end{pmatrix} \cdot \Delta$$

$$= \frac{Te}{4\Delta} \begin{pmatrix} b_1\ b_1 & b_1\ b_2 & b_1\ b_3 \\ b_2\ b_1 & b_2\ b_2 & b_2\ b_3 \\ b_3\ b_1 & b_3\ b_2 & b_3\ b_3 \end{pmatrix}$$

In the same way, we have

$$\iint Te \frac{\partial[N]^T}{\partial y} \frac{\partial[N]}{\partial y} \, d\Omega e$$

$$= \frac{Te}{4\Delta} \begin{pmatrix} c_1\ c_1 & c_1\ c_2 & c_1\ c_3 \\ c_2\ c_1 & c_2\ c_2 & c_2\ c_3 \\ c_3\ c_1 & c_3\ c_2 & c_3\ c_3 \end{pmatrix}$$

In order to evaluate the integral

$$\iint [N]^T [N] \, d\Omega e \qquad (37)$$

We can use the formula

$$\iint N_1^i N_2^j N_3^k \, d\Omega e = \frac{i!j!k!}{(i!+j!+k!+2)} 2\Delta \tag{38}$$

Integration Formula (38) is valid for two-dimensional elements.

Using Formula (38), the integral

$$\iint [N]^T [N] \, d\Omega e \tag{39}$$

is as follows :

$$\iint [N]^T [N] \, d\Omega e = \begin{pmatrix} \iint N_1^2 d\Omega e & \iint N_1 N_2 \, d\Omega e & \iint N_1 N_3 \, d\Omega e \\ \iint N_2 N_1 d\Omega e & \iint N_2^2 d\Omega e & \iint N_2 N_3 \, d\Omega e \\ \iint N_3 N_1 d\Omega e & \iint N_3 N_2 d\Omega e & \iint N_3^2 d\Omega e \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{6} & \frac{1}{12} & \frac{1}{12} \\ \frac{1}{12} & \frac{1}{6} & \frac{1}{12} \\ \frac{1}{12} & \frac{1}{12} & \frac{1}{6} \end{pmatrix} \Delta \tag{40}$$

Assembling the element "stiffness" matrix and "force" vector, we obtain

$$[K] \{h\} = \{f\} \tag{41}$$

Where $[K] = \sum_e [Ke]$: the global "stiffness" matrix

$\{f\} = \sum_e \{fe\}$: the global "force" vector

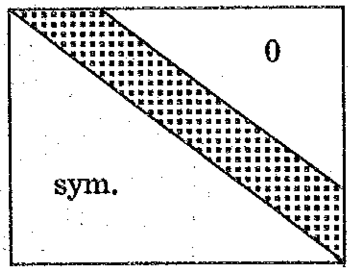
$\{h\} = \sum_e \{he\}$

Solving above the matrix equation, we obtain unknown heads.

(3)   Soltion of the Matrix Equation

The systems of equations obtained in the most practical problems are not only symmetric but also banded matrix which may be written as

A =



In this case, we can solve the matrix equations quickly and reduce the capacity of the computer memory.

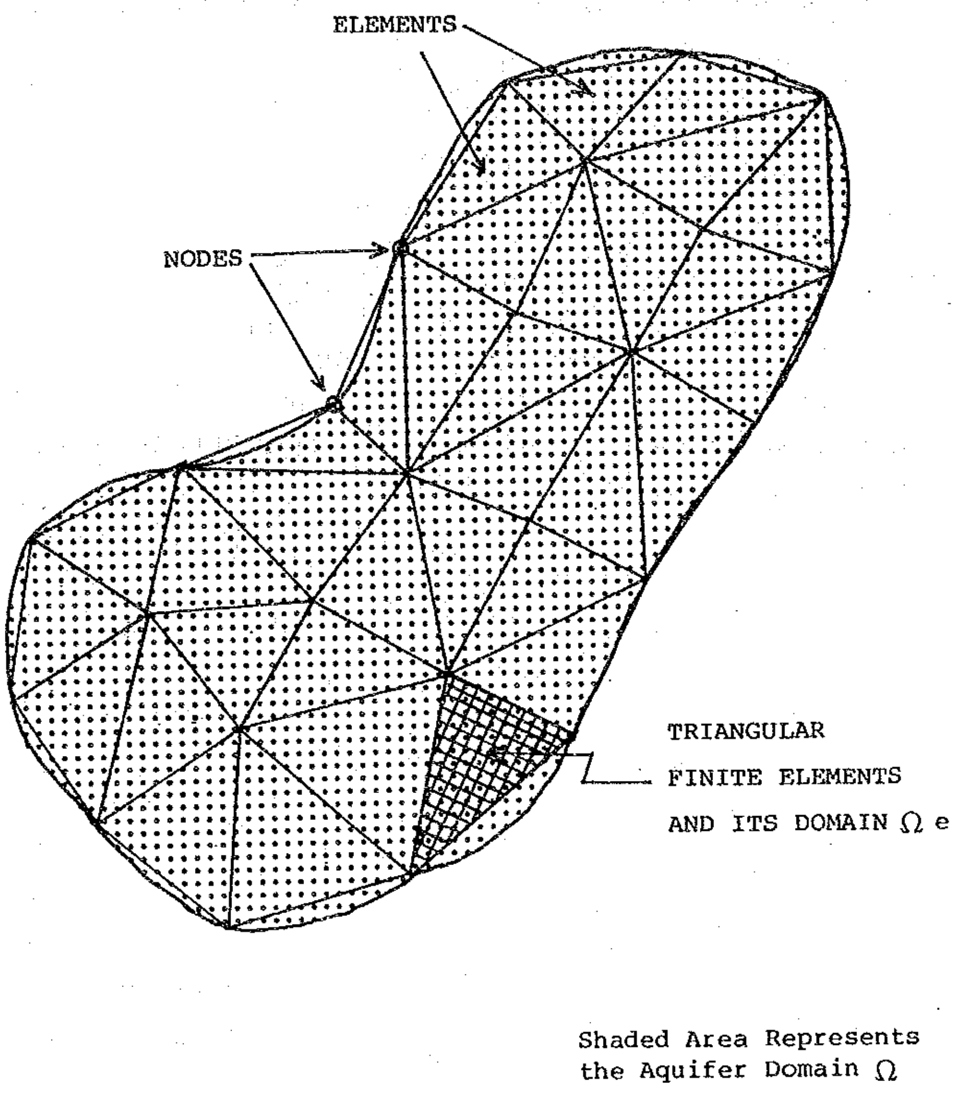
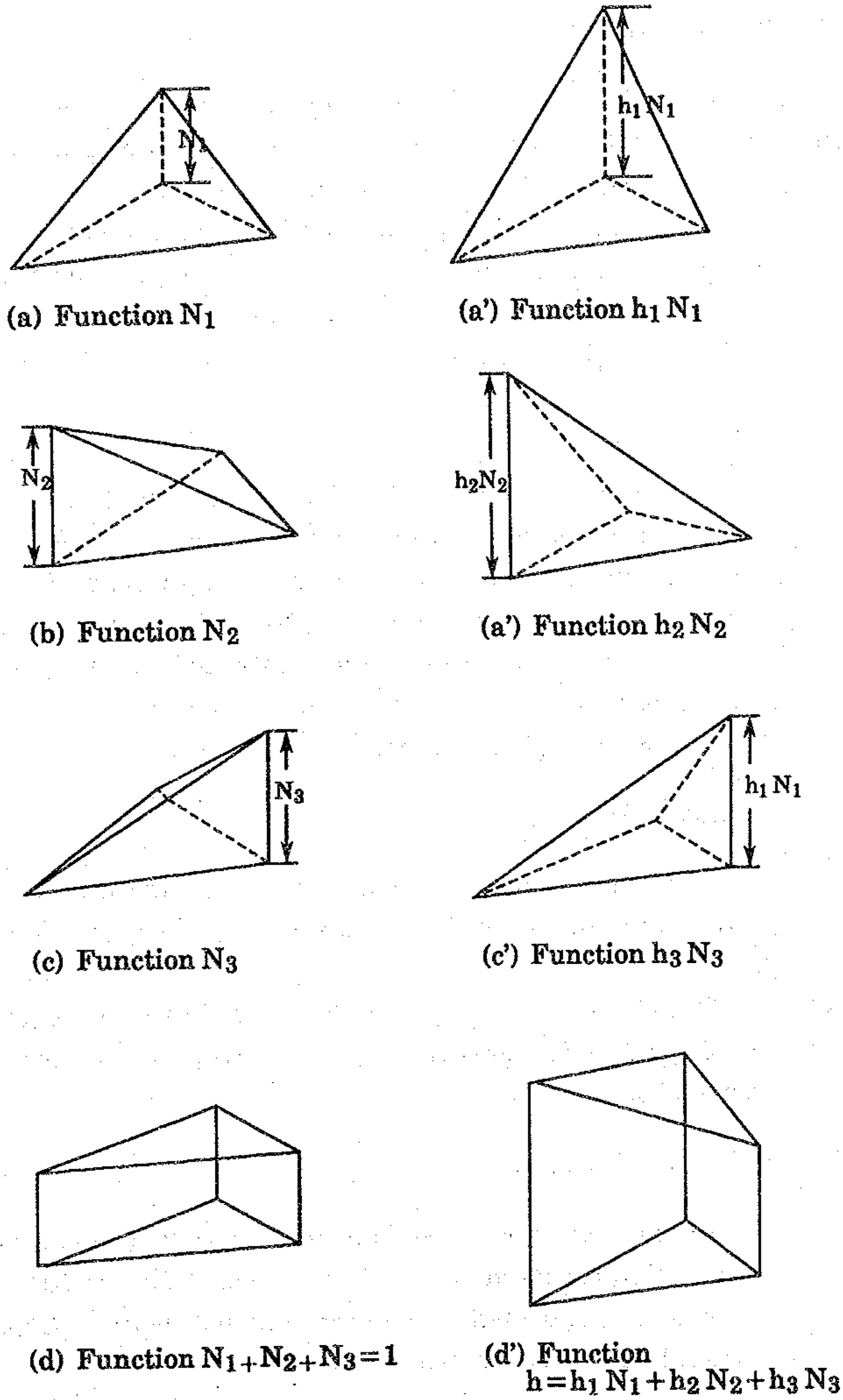


Fig. 2-13 Example of Aquifer Domain



(a) Function N_1 (a') Function $h_1 N_1$

(b) Function N_2 (a') Function $h_2 N_2$

(c) Function N_3 (c') Function $h_3 N_3$

(d) Function $N_1 + N_2 + N_3 = 1$ (d') Function $h = h_1 N_1 + h_2 N_2 + h_3 N_3$

Figure 2-14 Linear Shape Function for Triangular Elements

2-5 CASE STUDY OF SOME GROUNDWATER BASINS IN JAPAN

2-5-1 KUMAMOTO PLAIN

Kumamoto City is located in the western part of the Aso Volcano, Kyushu Island, in the south-western part of Japan. The municipal water supply is obtained from production wells in the lava flow deposits and unconsolidated delluvial deposits within the city. The municipal water supply has been obtained from three major pumping centers, which are Kengun, Kashima and Nuyamazu. The average daily groundwater withdrawal of the three pumping centers is 120,000m^3 / day in 1980 and is supposed to rise to 250,000m^3 / day in 1990.

(1) Hydrogeology

As shown in Figures 2-15 and b kumamoto Plain is covered mostly by volcanic deposits such as lava flow (To) and welded tuff (ASO-3, ASO-4). Togawa lava flow constitutes the main aquifer, and alluvial clayey sediments and most of the ASO-3 and ASO-4 constitute aquitards.

Water occurs in leaky artesian conditions, and recharge is derived from the lateral flow through the Mt. Aso recharge area and the vertical leakage flow through aquitards.

(2) Simulation Model

It is possible to simulate the complex aquifer conditions with simple multi-layered aquifer model systems as shown in Figure 2-15 and Figure 2-16.

The Model has two aquifers (TO-1, TO-2) and two aquitards (ASO-3, ASO-4) underlying phreatic aquifers (HO, TA) in which water tables assume to be constant.

(3) Hydrologic Constants

Based on aquifer and well production test data, average transmissivity and storativity of the main aquifer are 5000m^2/day and $3x10^{-3}$ respectively. The average permeability of unconsolidated deposits (aquitards) range between $1.8x10^{-4}$ and $2.0x10^{-4}$m/day.

(4) Subdivision of the Area

Finite element subdivision for the model aquifer on the Kumamoto Plain is shown in Figure 2-17.

The model has 292 triangular elements and 160 nodes. The three pumping area were subdivided more minutely and production wells were represented at each node.

(5) Verification of the Model

The accuracy and reliability of the model were assessed by a study of records on past pumpage and water levels. Water level declines and a piezometric surface map obtained by the simulation model were compared with actual water level declined and piezometric surface map for January 1978. As shown in Figure 2-18 and Figure 2-19, differences in the computed water level and the actual one are not significant when considered in relation to the accuracy and adequacy of hydrogeologic data (Figure 2-20).

(6) Prediction of Future Water Level

It is reasonable to assume that the simulation model may be used to predict, with reasonable accuracy, the effects of future groundwater development and the practical sustained yield of the aquifer. Simulation was carried out to understand the effects and influence of a selected scheme of pumping conditions. A water level decline map based on computer simulation for the present maximum withdrawal (A-plan) is shown in Figure 2-21. Results of the simulation are summarized and evaluated as shown in Table 2-2.
It is concluded that it is feasible to develop proposed pumping rate without significant influence on production wells and adjacent existing water utilization systems.

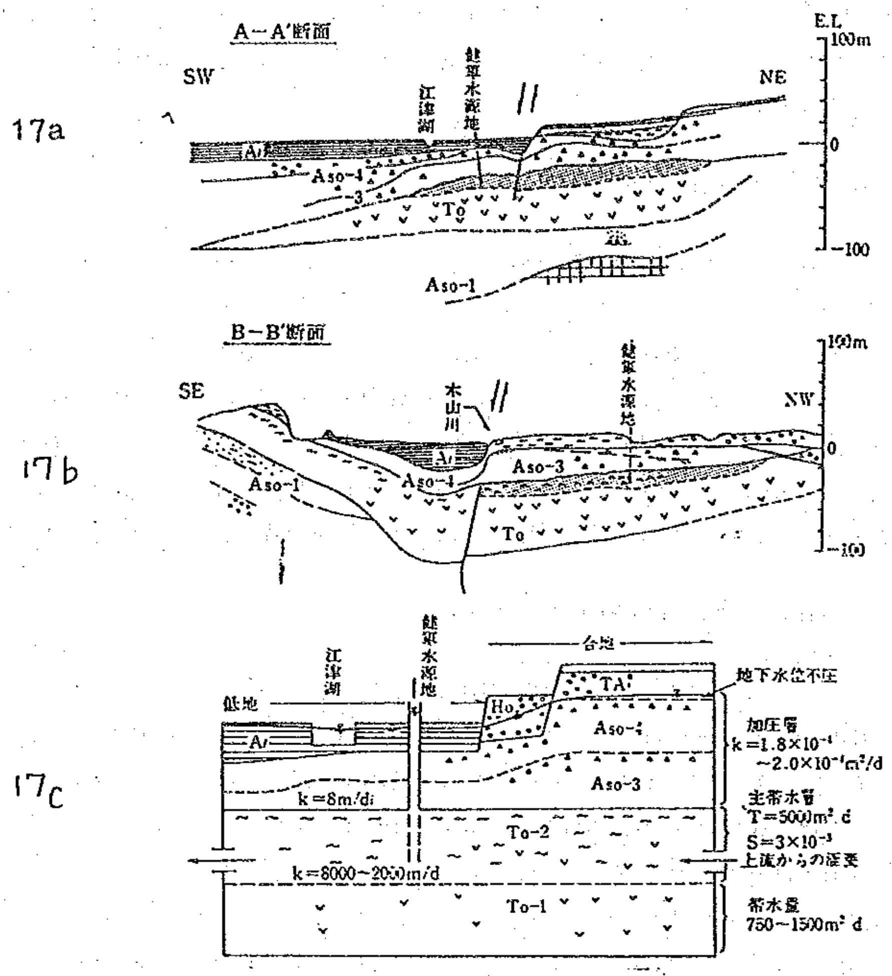


Fig. 2-15 Hydrogeological Model of Kumamoto Plain

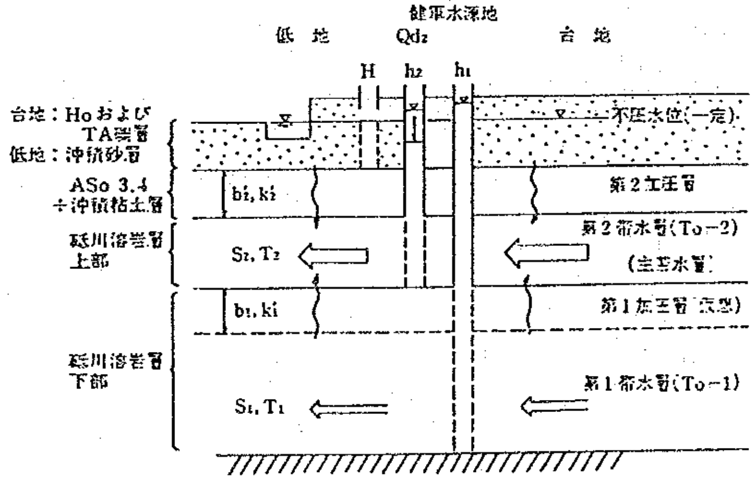


Fig. 2-16 Multi-layered aquifer system of Kumamoto Plain

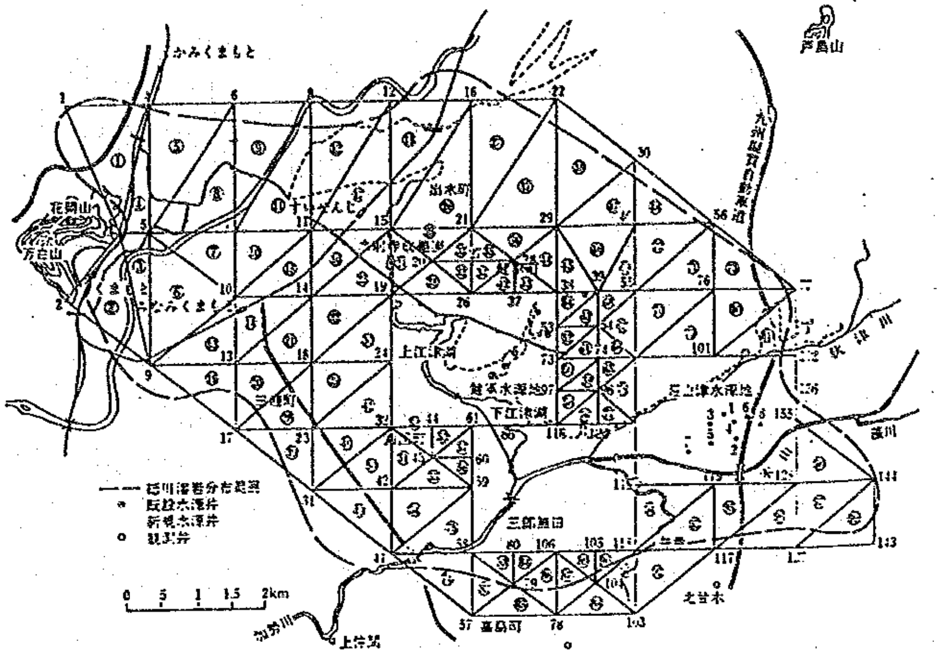


Fig. 2-17a Finite Element Network

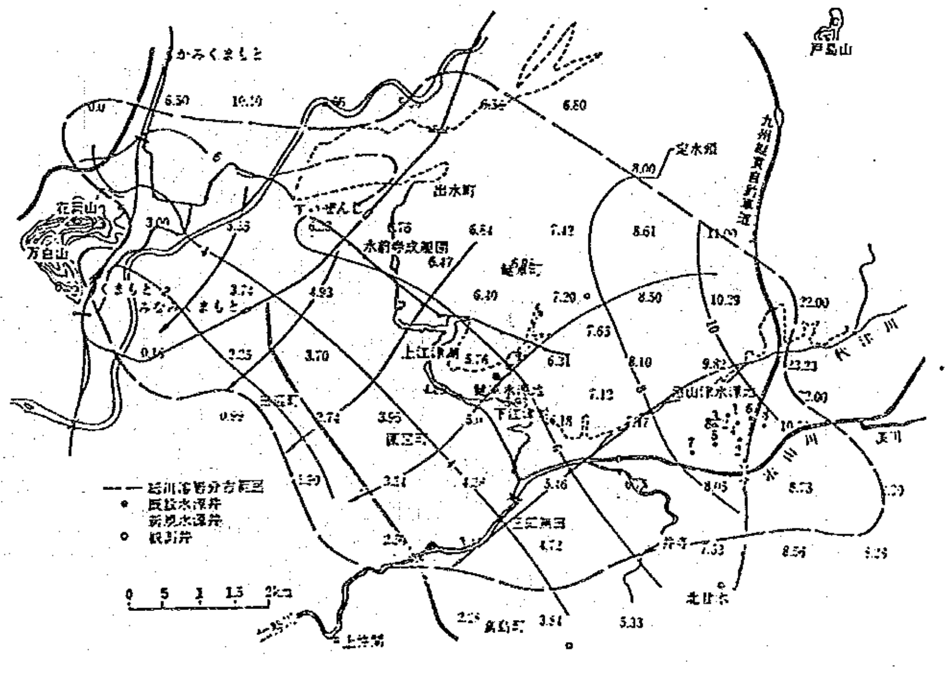


Fig. 2-17b Piezometric Surface Map (Initial condition)

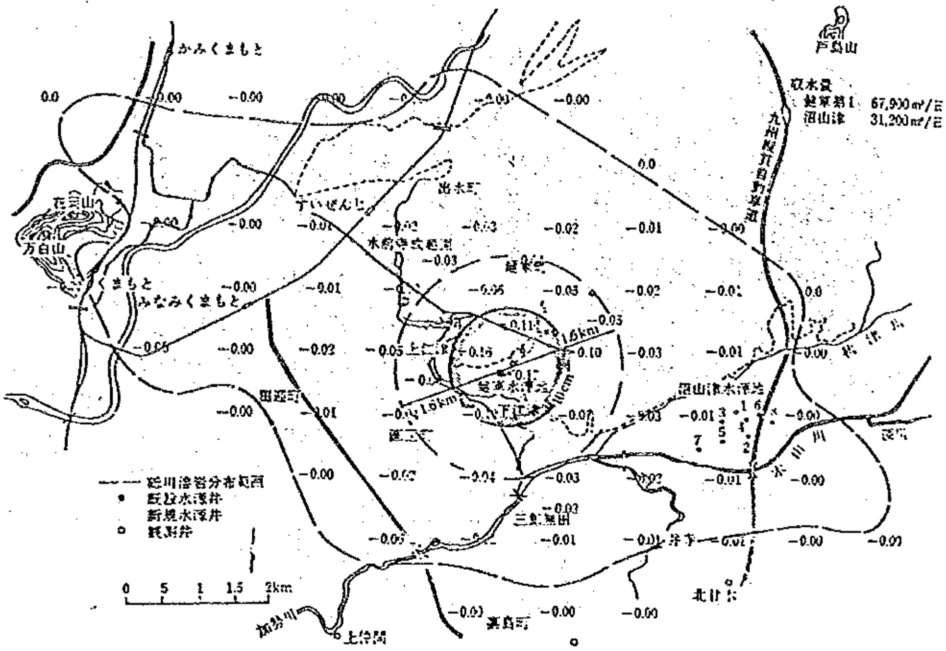


Fig. 2-18 Computed Water Level Decline

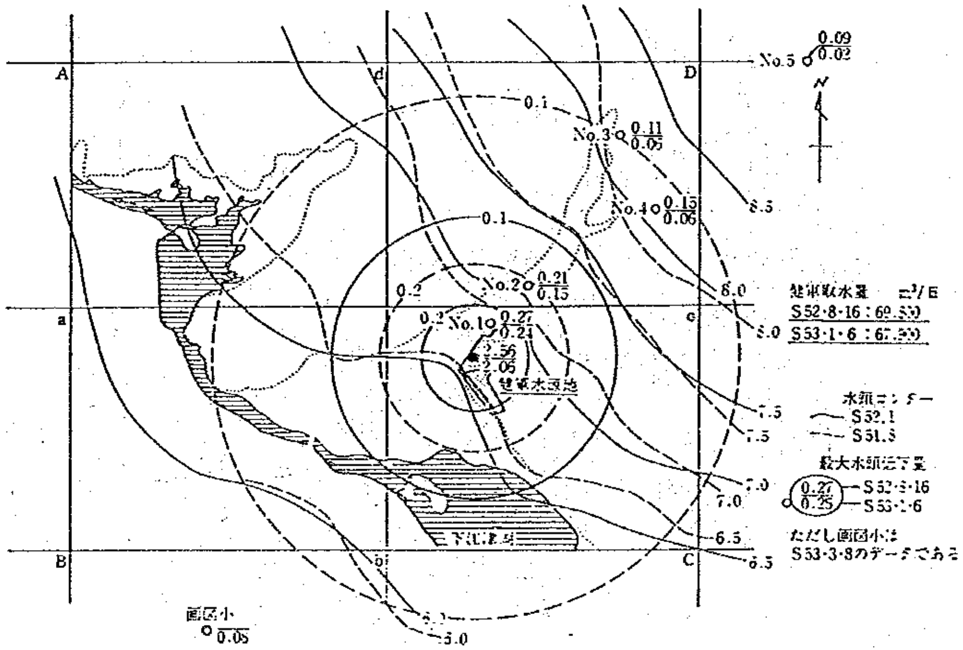


Fig. 2-19 Actual Groundwater Level Decline and Piezometric Surface

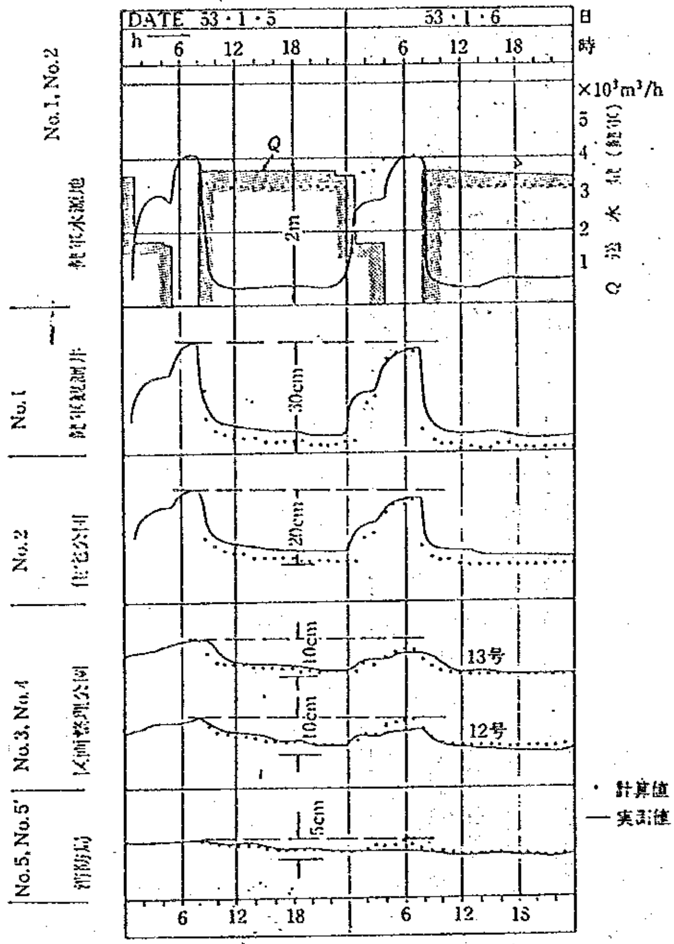


Fig. 2-20 Comparision between Actual Groundwater Head and Computed Groundwater Head

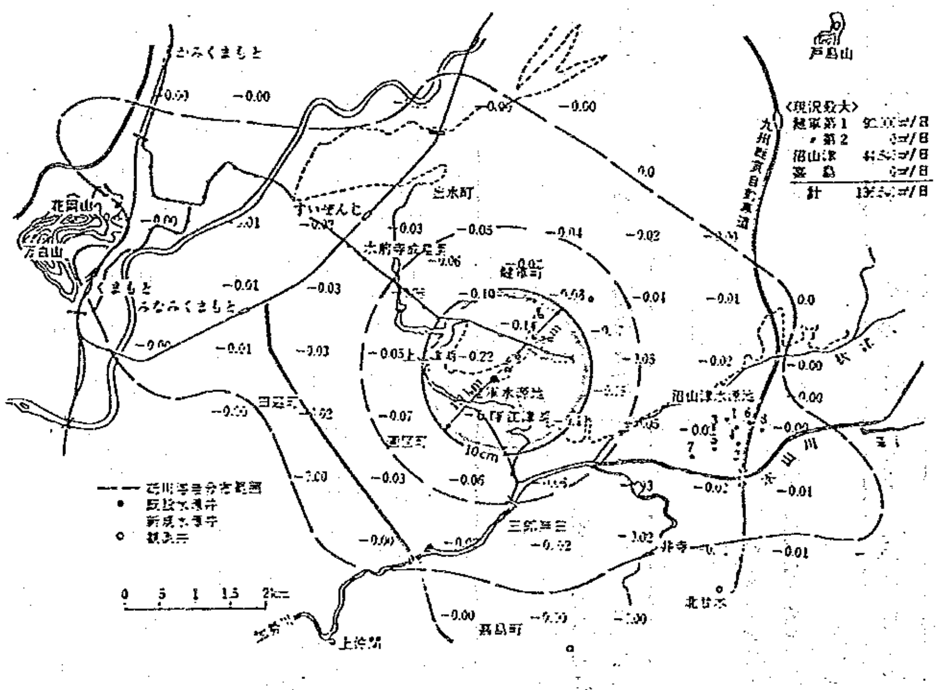


Fig. 2-21 Water Level Decline Map by Proposed Pumping Scheme

Table 2-2 Response and Evaluation of Simulation

Name of Plan	Pumping Withdrawal (m3/day)			Response and Evaluation		
Pumping Center	Kengun	Nuyamazu	Kasima	Kengun	Nuyamazu	Kasima
A Plan Present Maximum Withdrawal	92,000	44,640	0	Adjacent area is slightly affected by pumping. Radius of influence circle is 1.3 ~1.1km in 10cm drawdown.	not affected	Affected by Kengun in 4cm drawdown
B Plan 4th-Extension	101,000	54,720	50,160	Adjacent area is little affected by extension. "R" is 1.4~1.21km in 10cm drawdown.	Same as A plan	Affected by Kengun in 5cm drawdown

2-5-2 THE NOBI PLAIN

(1) Land Subsidence

The Nobi Plain is located in the central part of Japan and is about 1,300km^2 in area (Figure 2-22). There are over 5 million people living on the plain which is one of the important industrial areas in Japan.

In 1959, a typhoon occurred on the plain on September 26, which inflicted great damages. After this typhoon, a wide area of the plain was submerged for a long time. By this submergence, it was evident that an area of 186km^2 was below the mean sea level at that time.

The yearly rates of subsidence on this plain were 1-2cm during the period from 1950 to 1960, 2-4cm during the period from 1960 to 1965, and more than 10cm at certain places during the period from 1965 to 1975. (Figure 2-23) As of 1977, maximum subsidence exceeded 100cm. For such subsidence, more than 270km^2 of land had subsided below the mean sea level by 1980 (Figure 2-24).

(2) Withdrawal of Groundwater

The cause of this subsidence is the increasing withdrawal of groundwater. In 1960, the groundwater withdrawal on this plain was 850,000m^3 /day. The amount of pumpage increased rapidly in the 1960's, and the withdrawal reached 3,500,000m^3 / day in 1973 (Figure- 2-25).
The major use of groundwater is industrial, which amounts to 60% of the total with agricultural use of groundwater close to 20%.

(3) Water Level

Increasing withdrawal of groundwater has caused the steep decline in the water level. In 1973, water level in the 1st confined aquifer dropped to the level of 30m below ground, and that of the 2nd aquifer dropped to -40m (Figure 2-26, Figure 2-27).

(4) Subsurface Geology

The Nobi Plain is underlain by younger sediments (Tertiary to Quarternary). The yearly decline in the water level has caused compaction of these sediments.

The subsurface stratigraphy on this plain is shown in Table 2-3. The Tertiary and the younger sediments are composed of an alternation of clay, sand and gravel beds (Figure 2-28). These gravel beds (G1, G2, G3) are main aquifers on the plain. The clay beds (H, D3) overlying the gravel beds, are aquitards and very compressive. The distribution of thickness of clay beds are shown in Figure 2-29.

(5) Groundwater Simulation

For the purpose of preventing land subsidence, we executed an investigation sponsored by the Aichi Prefecture and the Chubu Regional Construction Bureau within the Ministry of Construction. The investigation consisted of pumping tests, hydrogeological analysis and model simulation. The model simulation was aimed at simulating the groundwater flow and the subsidence, and to determine the withdrawal which would cease the land subsidence.

On the basis of the hydrogeological structure, we constructed a digital computer simulation model which consisted of quasi three-dimensional multi-aquifer by the Finite Element Method (Figure 2-30).

In calibrating the model with the observed water level and subsidence, we incorporated future withdrawal plans into it. Based on the response of the model, we were able to determine a safe yield (Figure 2-31).

Presently, withdrawal of groundwater on the plain is being controlled by the regulations set up by the authorities, and the land subsidence has ceased.

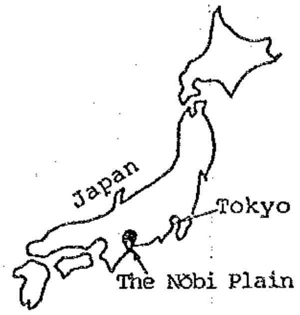


Fig. 2-22 The Nobi Plain

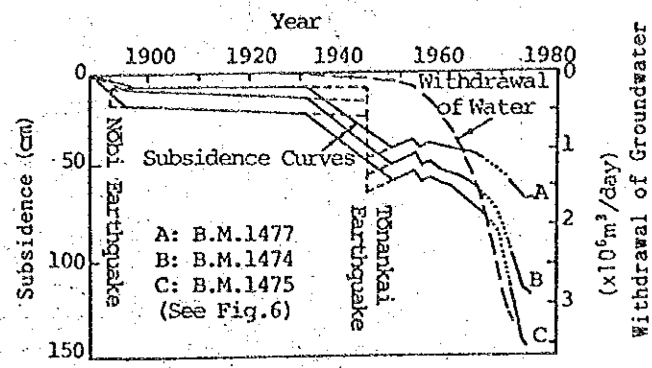


Fig. 2-23 Subsidence of Bench Marks and Withdrawal of Groundwater on the Nobi Plain

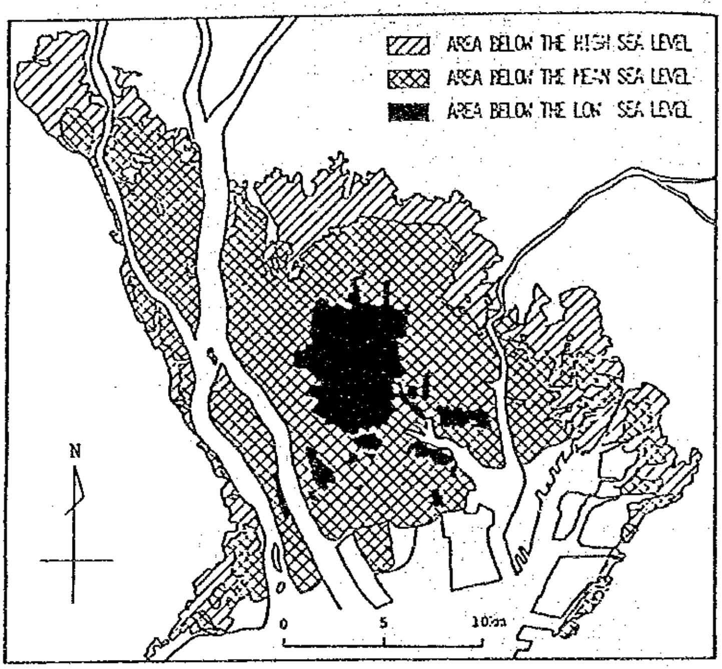


Fig. 2-24 Area below the Sea Level on the Nobi Plain

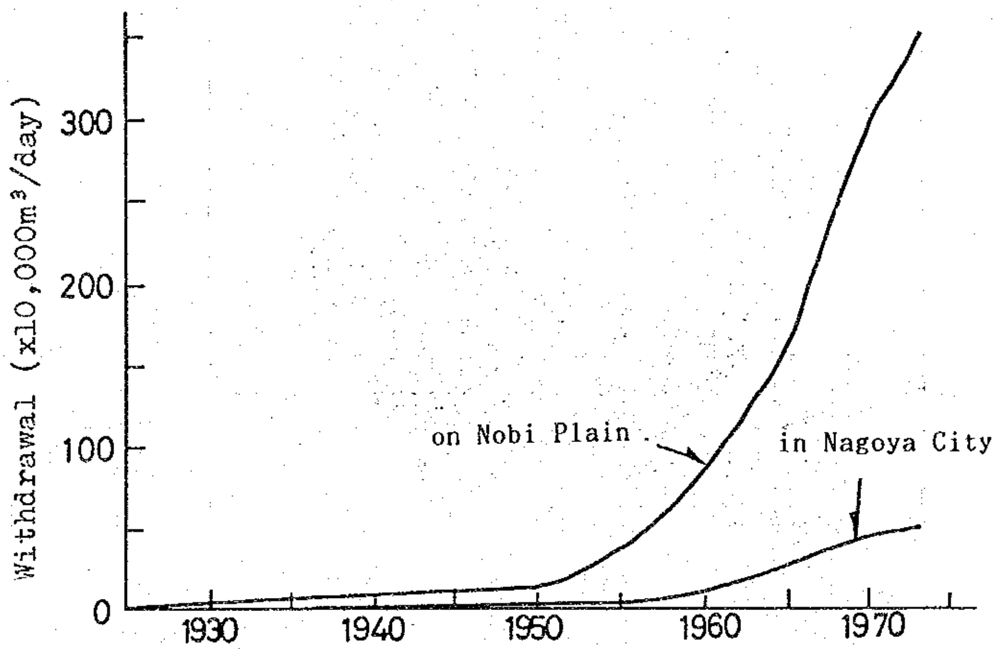


Fig. 2-25 Withdrawal of Groundwater on the Nobi Plain

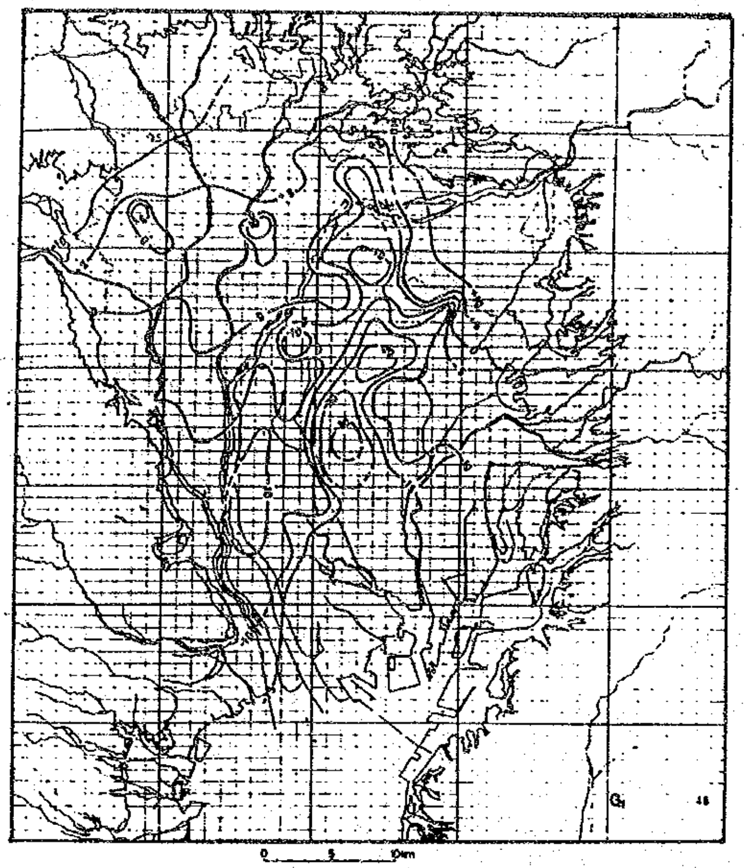


Fig. 2-26 Piezometric Head of 1st Confined Aquifer (G1) in 1973

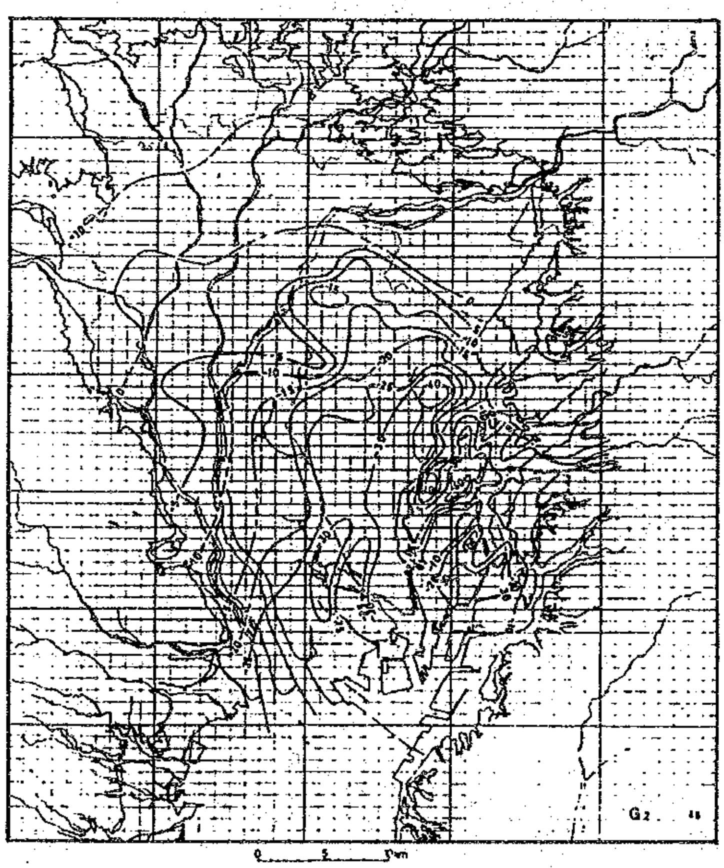


Fig. 2-27 Piezometric Head of 2nd Confined Aquifer (G2) in 1973

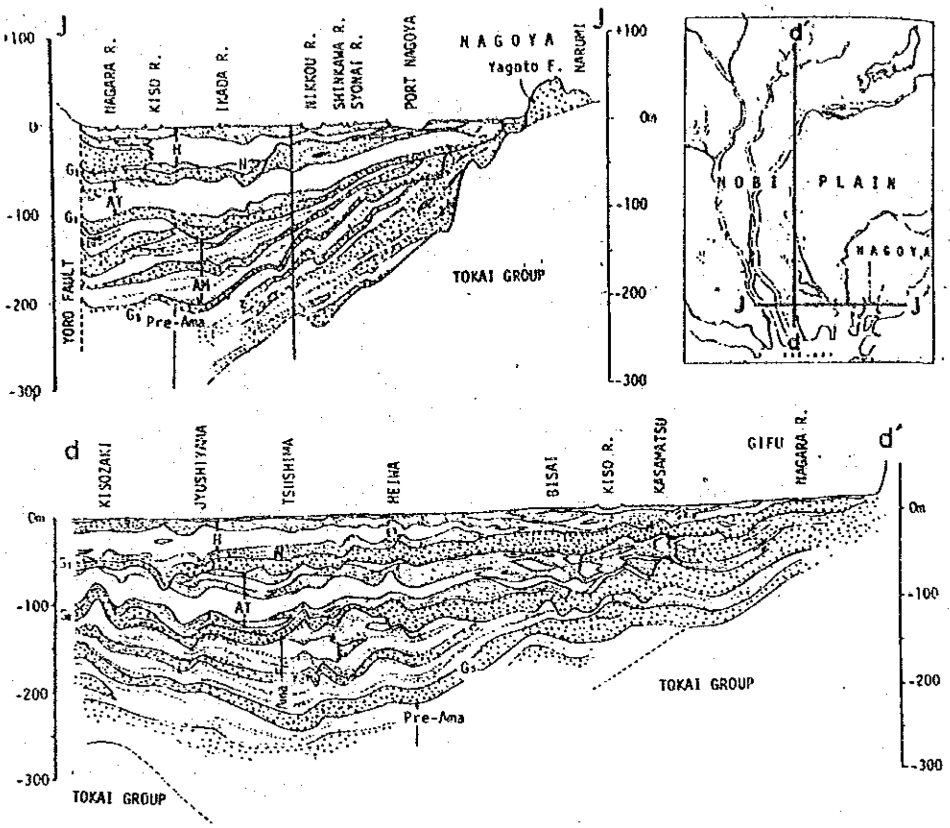


Fig. 2-28 Geologic Cross Section of the Nobi Plain

H : Nanyo Formation (Holocene), N : Nobi F., AT : Atsuta Foramation, Dotted : gravel, Fine dotted : sand, Blank : clay

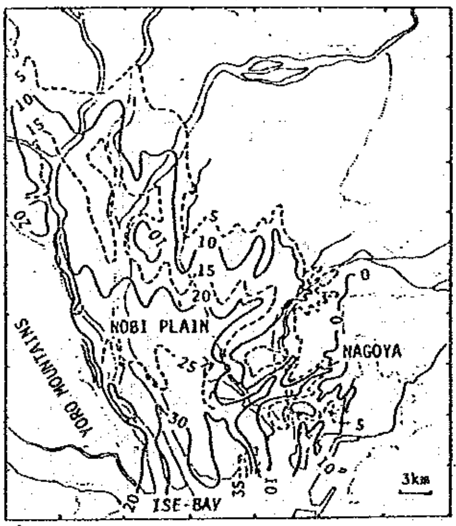


Fig. 2-29a Distribution of Thickness of the Holocene Marine Clay Bed, AL

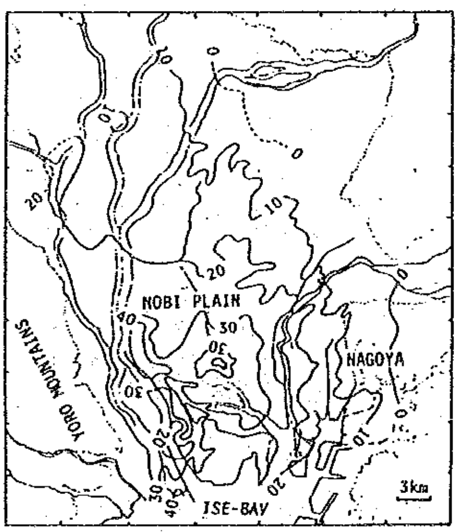


Fig. 2-29b Distribution of Thickness of the Lower Marine Clay Bed, D3L, in the Atsuta Foramation (in meter)

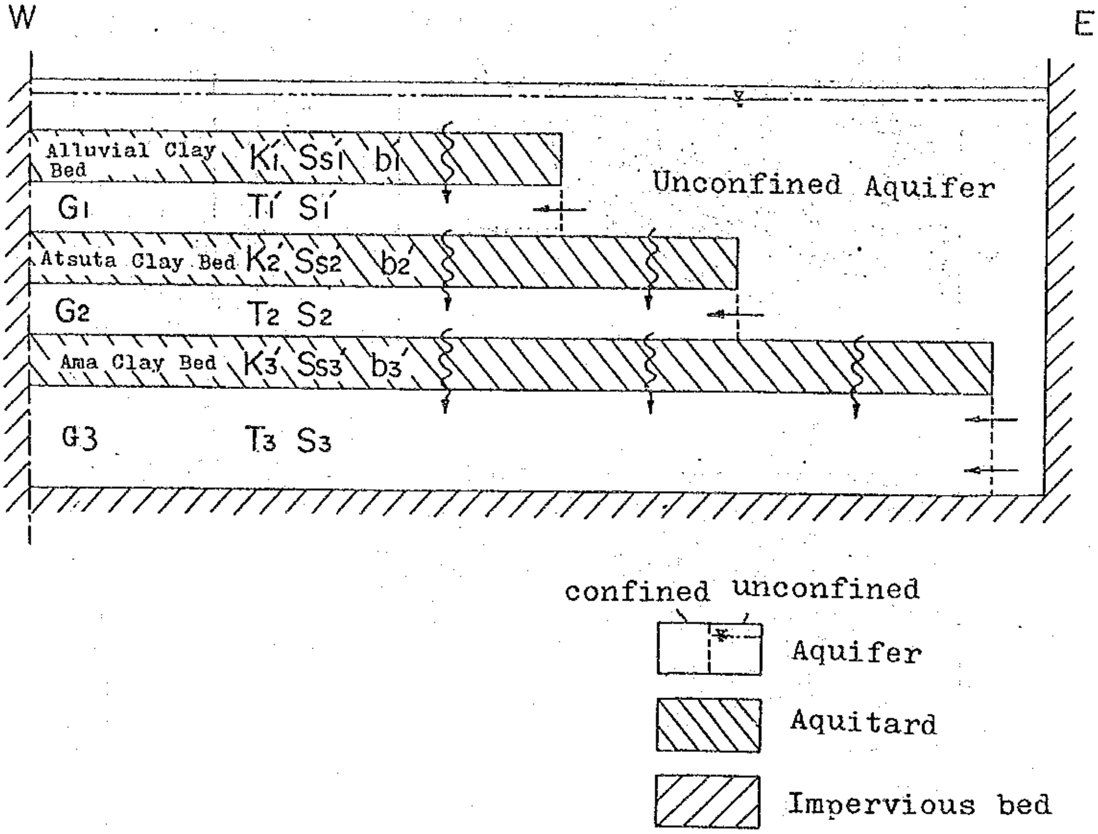


Fig. 2-30 a Quasi Three-Dimensional Multi-Aquifer Model

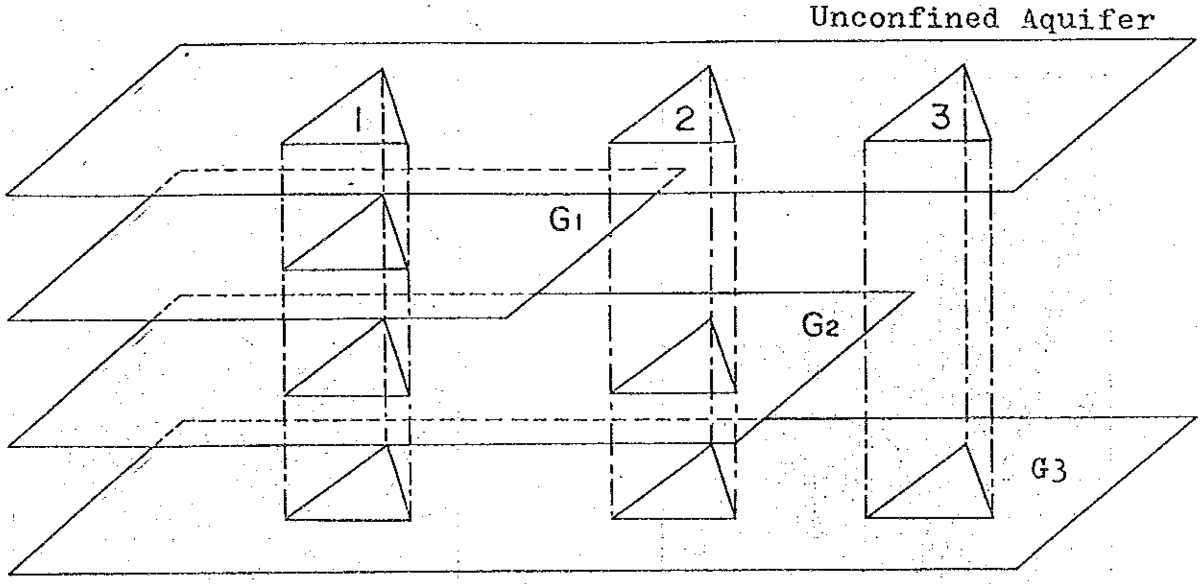


Fig. 2-30 b Finite Element Network

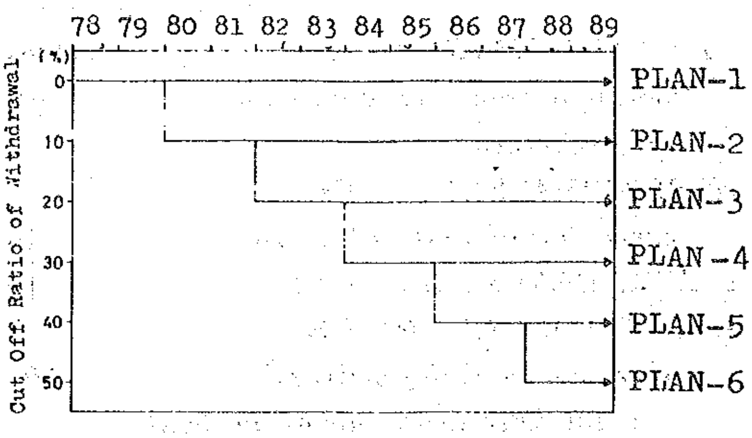


Fig. 2-31a Plans for Future Withdrawal of Groundwater

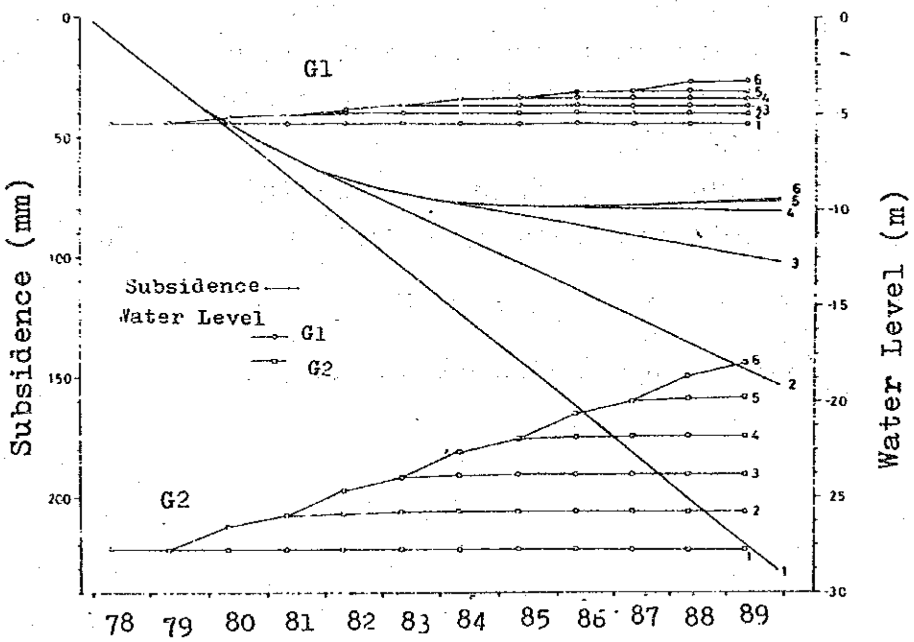


Fig. 2-31b Calculated Water Level and Subsidence

Table 2-3 The Subsurface Stratigraphy on the Nobi Plain

			(Thickness)
HOLOCENE	NANYO FORMATION	(H)	
	(loose upper sand bed and very soft marine clay bed)		10 - 60 m
PLIESTOCENE	NOBI FORMATION	(N)	
	(alternation of sand and silt bed)		10 - 20 m
	DAIICHI GRAVEL BED	(G_1)	10 - 30 m
	ATSUTA FORMATION	(D_3)	
	(upper sand and clay beds and unconsolidated lower marine clay bed)		10 - 100 m
	DAINI GRAVEL BED	(G_2)	5 - 30 m
	AMA FORMATION GROUP		
	(alternations of semiconsolidated sand, clay and gravel beds)		30 - 100 m
	PRE-AMA FORMATION GROUPS		
	(alternations of semiconsolidated sand, clay and gravel beds)		30 - 70 m
PLIOCENE	TOKAI GROUP		
	(alternations of semiconsolidated 200 - 100 m clay, sand and gravel beds)		200 - 1000 m

MIOCENE SERIES

PRE-TERTIARY BASEMENT ROCK

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3. QUASI-THREE DIMENSIONAL MULTI AQUIFER MODEL BY FINITE ELEMENT METHOD

```
C
C      ******************************
C      *                            *
C      *  QUASI-THREE DIMENSIONAL   *
C      *     MULTI AQUIFER MODEL    *
C      * BY FINITE ELEMENT METHOD   *
C      *JICA, K.FUJISAKI, T.MAEKAWA*
C      ******************************
C
      COMMON NEL,NNO,NSTEPS,ID,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *       DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *       H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *       B(500,4),D(7,2),E(7),NBAND
      COMMON LYL(450,4),         NWEL,ST(500),NOB(40),SJ(40),
     *       HJ(40,4),    HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *       LBL(287),NL(15),NLE(15,50),NLP(15,50),IHW
      REAL*4 KD,L,QIN(450),RIN(450)
      REAL*8 F,G
C
      ACCEPT *,NFUTU
      ACCEPT *,QMULT
C
      CALL GDATA
      IF(IP) 20,20,10
   10 CONTINUE
   20 CALL FORMK
C
      DO 1000 N=1,NSTEPS
C
      IF(NFUTU.EQ.1.OR.N.EQ.1) THEN
      IF(IHW.EQ.1) THEN
      DO 100 I=1,ID
      READ(16) (QIN(J),J=1,NEL)
      IF(N.EQ.1)READ(15) (RIN(J),J=1,NEL)
      DO J=1,NEL
      Q(J,I)=QIN(J)*QMULT-RIN(J)
      END DO
  100 CONTINUE
      END IF
      END IF
C
      NT=N
      DO 500 M=1,4
      CALL CALAH(NT)
  500 CONTINUE
 1000 CONTINUE
C---------------------------
 2000 STOP
      END
```

```
      SUBROUTINE FORMK
C
C     ************************************
C     *                                  *
C     * SUB PROGRAM TO FORM GLOBAL MATRIX *
C     *                                  *
C     ************************************
C
      COMMON NEL,NNO,NSTEPS,IL,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *       DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *       H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *       B(500,4),D(7,2),R(7),NBAND
      COMMON LYL(450,4),         NWEL,ST(500),NOB(40),SJ(40),
     *       HJ(40,4),    HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *       LBL(287),NL(15),NLE(15,50),NLP(15,50),IHW
      DIMENSION E(4,4)
      REAL*4 KD,L
      REAL*8 F,G,E
      DO 100 I=1,NNO
      DO 100 J=1,NBAND
      DO 100 K=1,IL
  100 G(I,J,K)=0.0
      DO 1500 ID=1,IL
      DO 1000 N=1,NEL
      CALL STIFF(E,ID,N)
      DO 200 I=1,4
      II=NOP(N,I)
      DO 200 J=1,4
      JJ=NOP(N,J)
      LL=JJ-II+1
      IF(LL-NBAND) 210,210,2000
  210 IF(LL)        200,200,220
  220 G(II,LL,ID)=G(II,LL,ID)+E(I,J)
  200 CONTINUE
 1000 CONTINUE
      NNC=NC(ID)
      IF(NNC) 350,350,310
  310 DO 300 I=1,NNC
      J=NOC(I,ID)
      G(J,1,ID)=G(J,1,ID)*10.0**8
  300 CONTINUE
  350 CALL SOLV1(ID)
 1500 CONTINUE
      RETURN
 2000 WRITE(6,601) N
  601 FORMAT(/10X,'ERROR IN BAND WIDTH NO.',I4)
      STOP
      END
```

```
      SUBROUTINE STIFF(E,ID,N)
C
C     ******888888*************************
C     *                                   *
C     * SUB PROGRAM TO FORM ELEMENT MATRIX *
C     *                                   *
C     *************************************
C
      COMMON NEL,NNO,NSTEPS,IL,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *       DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *       H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *       B(500,4),D(7,2),R(7),NBAND
      COMMON LYL(450,4),           NWEL,ST(500),NOB(40),SJ(40),
     *       HJ(40,4),    HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *       LBL(287),NL(15),NLE(15,50),NLP(15,50),IHW
      DIMENSION E(4,4)
      REAL*4 KD,W
      REAL*8 F,G,E
      I=NOP(N,1)
      J=NOP(N,2)
      K=NOP(N,3)
      L=NOP(N,4)
      P1=T(N,ID)*DY/DX/6.0
      P2=T(N,ID)*DX/DY/6.0
      P4=DX*DY*S(N,ID)/DT/36.0
      P3=0.0
      IF(ID-1) 50,50,70
   50 LL=LYL(N,ID)
      IF(LL)110,110,80
   80 GO TO (100,110),LL
   70 CONTINUE
      IF(LYL(N,ID)) 110,110,100
  100 P3=(KD(I,ID)+KD(J,ID)+KD(K,ID)+KD(L,ID))/(B(I,ID)+B(J,ID)+
     *                                              B(K,ID)+B(L,ID))
  110 IF(ID+1-IL) 120,120,140
  120 IF(LYL(N,ID+1)) 140,140,130
  130 P3=P3+(KD(I,ID+1)+KD(J,ID+1)+KD(K,ID+1)+KD(L,ID+1))/
     *                      (B(I,ID+1)+B(J,ID+1)+B(K,ID+1)+B(L,ID+1))
  140 P3=P3*DX*DY/36.0
      E(1,1)=2.0*P1+2.0*P2+4.0*P3+4.0*P4
      E(1,2)=-2.0*P1+P2+2.0*P3+2.0*P4
      E(1,3)=-P1-P2+P3+P4
      E(1,4)=P1-2.0*P2+2.0*P3+2.0*P4
      E(2,2)=E(1,1)
      E(3,3)=E(1,1)
      E(2,1)=E(1,2)
      E(3,4)=E(1,2)
      E(4,4)=E(1,1)
      E(4,3)=E(1,2)
      E(2,4)=E(1,3)
      E(3,1)=E(1,3)
      E(4,2)=E(1,3)
      E(2,3)=E(1,4)
      E(3,2)=E(1,4)
      E(4,1)=E(1,4)
      RETURN
      END
```

```
      SUBROUTINE SOLV1(ID)
C
C     ***************************
C     *                         *
C     * TO REDUCE GLOBAL MATRIX *
C     *                         *
C     ***************************
C
      COMMON NEL,NNO,NSTEPS,IL,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *       DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *       H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *       B(500,4),D(7,2),E(7),NBAND
      COMMON LYL(450,4),          NWEL,ST(500),NOB(40),SJ(40),
     *       HJ(40,4),   HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *       LBL(287),NL(15),NLE(15,50),NLP(15,50),IHW
      REAL*4 KD,R
      REAL*8 F,G
      DO 300 N=1,NNO
      I=N
      DO 290 L=2,NBAND
      I=I+1
      IF(G(N,L,ID)) 240,290,240
  240 C=G(N,L,ID)/G(N,1,ID)
      J=0
      DO 270 K=L,NBAND
      J=J+1
      IF(G(N,K,ID)) 260,270,260
  260 G(I,J,ID)=G(I,J,ID)-C*G(N,K,ID)
  270 CONTINUE
      G(N,L,ID)=C
  290 CONTINUE
  300 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALAH(NT)
C
C     ***********************************
C     *                                 *
C     * TO CALCULATE WATER HEAD BY AQUIFER *
C     *                                 *
C     ***********************************
C
      COMMON NEL,NNO,NSTEPS,IL,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *        DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *        H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *        B(500,4),D(7,2),E(7),NBAND
      COMMON LYL(450,4),          NWEL,ST(500),NOB(40),SJ(40),
     *        HJ(40,4),   HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *        LBL(287),NL(15),NLE(15,50),NLP(15,50)
      COMMON /BK2/NNF,NFL(20,2),TR(20,60)
      REAL*4 KD,W
      REAL*8 F,G
      DO 1000 ID=1,IL
      IC=ID+2
      IE=ID+1
      DO 100  I =1,NNO
  100 F(I)=0.0
      DO 200 N=1,NEL
      I=NOP(N,1)
      J=NOP(N,2)
      K=NOP(N,3)
      L=NOP(N,4)
      P4=DX*DY*S(N,ID)/DT/36.0
      Q4=Q(N,ID)*0.25
C
  110 F(I)=F(I)+P4*(4.0*H(I,IE)+2.0*H(J,IE)+    H(K,IE)+2.0*H(L,IE))-Q4
      F(J)=F(J)+P4*(2.0*H(I,IE)+4.0*H(J,IE)+2.0*H(K,IE)+    H(L,IE))-Q4
      F(K)=F(K)+P4*(    H(I,IE)+2.0*H(J,IE)+4.0*H(K,IE)+2.0*H(L,IE))-Q4
      F(L)=F(L)+P4*(2.0*H(I,IE)+    H(J,IE)+2.0*H(K,IE)+4.0*H(L,IE))-Q4
C
      IF(ID-1) 150,150,190
  150 LL=LYL(N,ID)
      IF(LL) 202,202,160
  160 GO TO (201,205),LL
  190 CONTINUE
      IF(LYL(N,ID)) 202,202,201
  201 P3=DX*DY*(KD(I,ID)+KD(J,ID)+KD(K,ID)+KD(L,ID))/
     *                  (B(I,ID)+B(J,ID)+B(K,ID)+B(L,ID))/36.0
      F(I)=F(I)+P3*(4.0*H(I,ID)+2.0*H(J,ID)+    H(K,ID)+2.0*H(L,ID))
      F(J)=F(J)+P3*(2.0*H(I,ID)+4.0*H(J,ID)+2.0*H(K,ID)+    H(L,ID))
      F(K)=F(K)+P3*(    H(I,ID)+2.0*H(J,ID)+4.0*H(K,ID)+2.0*H(L,ID))
      F(L)=F(L)+P3*(2.0*H(I,ID)+    H(J,ID)+2.0*H(K,ID)+4.0*H(L,ID))
      GO TO 205
  202 F(I)=F(I)+V(ID,I)
      F(J)=F(J)+V(ID,J)
      F(K)=F(K)+V(ID,K)
      F(L)=F(L)+V(ID,L)
  205 IF(IC-5) 207,207,200
  207 IF(LYL(N,IE)) 209,209,208
  208 P3=DX*DY*(KD(I,IE)+KD(J,IE)+KD(K,IE)+KD(L,IE))/
     *                 (B(I,IE)+B(J,IE)+B(K,IE)+B(L,IE))/36.0
```

```
      F(I)=F(I)+P3*(4.0*H(I,IC)+2.0*H(J,IC)+    H(K,IC)+2.0*H(L,IC))
      F(J)=F(J)+P3*(2.0*H(I,IC)+4.0*H(J,IC)+2.0*H(K,IC)+    H(L,IC))
      F(K)=F(K)+P3*(    H(I,IC)+2.0*H(J,IC)+4.0*H(K,IC)+2.0*H(L,IC))
      F(L)=F(L)+P3*(2.0*H(I,IC)+    H(J,IC)+2.0*H(K,IC)+4.0*H(L,IC))
      GO TO 200
  209 F(I)=F(I)-U(IE,I)
      F(J)=F(J)-U(IE,J)
      F(K)=F(K)-U(IE,K)
      F(L)=F(L)-U(IE,L)
  200 CONTINUE
C
  220 NNC=NC(ID)
      IF(NNC) 270,270,250
  250 DO 260 I=1,NNC
      J=NOC(I,ID)
      F(J)=G(J,1,ID)*HC(I,ID,1)
  260 CONTINUE
  270 IF(ID-4) 300,275,300
  275 IF(NNF) 300,300,280
  280 DO 290 I=1,NNF
      J=NFL(I,1)
      K=NFL(I,2)
      F(J)=F(J)+TR(I,NT)*0.5
  290 F(K)=F(K)+TR(I,NT)*0.5
C
  300 CALL SOLV2(ID)
C
      DO 400 I=1,NNO
  400 H(I,IE)=(F(I)+H(I,IE))*0.5
 1000 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SOLV2(ID)
C
C     ***********************************
C     *                                 *
C     * TO SOLVE SIMULTANEOUS EQUATIONS *
C     *                                 *
C     ***********************************
C
      COMMON NEL,NNO,NSTEPS,IID,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *       DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *       H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *       B(500,4),D(7,2),E(7),NBAND
      COMMON LYL(450,4),       NWEL,ST(500),NOB(40),SJ(40),
     *       HJ(40,4),   HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *       LBL(287),NL(15),NLE(15,50),NLP(15,50),IHW
      REAL*4 KD,R
      REAL*8 F,G
      DO 300 N=1,NNO
      I=N
      DO 290 L=2,NBAND
      I=I+1
  290 F(I)=F(I)-G(N,L,ID)*F(N)
  300 F(N)=F(N)/G(N,1,ID)
C
      N=NNO
  350 N=N-1
      IF(N) 500,500,360
  360 L=N
      DO 400 K=2,NBAND
      L=L+1
      IF(G(N,K,ID)) 370,400,370
  370 F(N)=F(N)-G(N,K,ID)*F(L)
  400 CONTINUE
      GO TO 350
  500 RETURN
      END
```

```
      SUBROUTINE GDATA
C
C     ******************************
C     *                            *
C     * SUB PROGRAM FOR DATA ENTRY *
C     *                            *
C     ******************************
C
      COMMON NEL,NNO,NSTEPS,ID,NP,NE,G(500,29,4),T(450,4),S(450,4),
     *       DX,DY,DT,NOP(450,4),NC(4),NOC(80,4),F(500),Q(450,4),
     *       H(500,5),V(4,500),U(4,500),HC(80,4,144),KD(500,4),
     *       B(500,4),D(7,2),E(7),NBAND
      COMMON LYL(450,4),           NWEL,ST(500),NOB(40),SJ(40),
     *       HJ(40,4),   HDT,LXL(500,4),IP,H0(500,4),NBK,NLL,
     *       LBL(287),NL(15),NLE(15,50),NLP(15,50),IHW
      COMMON /BK2/NNF,NFL(20,2),TR(20,60)
      REAL*4 KD,L
      REAL*8 F,WNA(40),G
C
      ACCEPT *,IHIN                         !0:READ  >0:FILE
      ACCEPT *,TBAI                         !TO MODIFY T VALUE
      ACCEPT *,KBAI                         !TO MODIFY KD VALUE
C
      READ(17,100) NEL,NNO,ID,NSTEPS,NP,NE,NBAND,NWEL,IP,IHW,DX,DY,DT,
     *          NBK,NLL
  100 FORMAT(10I5,3F10.5/2I5)
  131 FORMAT(6F10.5)
C
      IF(NWEL) 190,190,180
  180 READ(17,136) (WNA(I),NOB(I),I=1,NWEL)
  190 CONTINUE
  136 FORMAT(5(A8,I4))
C
      READ(17,101) (NC(I),I=1,ID)
      DO 200 I=1,ID
      J=NC(I)
      IF(J) 200,200,201
  201 READ(17,102) (NOC(K,I),K=1,J)
      READ(17,103) (HC(K,I,1),K=1,J)
  200 CONTINUE
  101 FORMAT(4I5)
  102 FORMAT(20I4)
  103 FORMAT(20F4.0)
C
      READ(17,141) NNF
      IF(NNF) 400,400,410
  410 READ(17,142)((NFL(I,J),J=1,2),I=1,NNF)
      DO 420 I=1,NNF
  420 READ(17,143) (TR(I,J),J=1,NSTEPS)
  400 CONTINUE
  141 FORMAT(I5)
  142 FORMAT(20I4)
  143 FORMAT(10F8.0)
C
      IF(NBK.EQ.0) GO TO 500
      READ(3,138) (LBL(I),I=1,NEL)
      READ(3,146) (NL(I),I=1,NLL)
```

```
      DO 510 I=1,NLL
      J=NL(I)
  510 READ(3,147) (NLE(I,N),NLP(I,N),N=1,J)
  500 CONTINUE
  146 FORMAT(10I5)
  147 FORMAT(10(I4,I2))
C
      WRITE(6,104) NEL,NNO,ID,NSTEPS,NP,NE,NBAND,NWEL,IP,IHW,DX,DY,DT,
     *             NBK,NLL
      IF(NWEL) 205,205,204
  204 WRITE(6,137) (WNA(I),NOB(I),I=1,NWEL)
  205 CONTINUE
      WRITE(6,105) (I,NC(I),I=1,ID)
      DO 210 I=1,ID
      J=NC(I)
      IF(J) 210,210,211
  211 DO 212 K=1,J
  212 WRITE(6,106) I,NOC(K,I),(N,HC(K,I,N),N=1,NSTEPS)
  210 CONTINUE
      DT=DT/2.0
      HDT=DT/2.0
      IF(NNF) 430,430,440
  440 WRITE(6,144) NNF
      DO 435 I=1,NNF
  435 WRITE(6,145) (NFL(I,J),J=1,2),(J,TR(I,J),J=1,NSTEPS)
  430 CONTINUE
      IF(NBK.EQ.0) GO TO 550
      WRITE(6,148)
      DO 540 I=1,NLL
      J=NL(I)
  540 WRITE(6,149) I,(N,NLE(I,N),NLP(I,N),N=1,J)
  550 CONTINUE
  148 FORMAT(/10X,'<PERIMETER OF FLOW CALCULATION>'/)
  149 FORMAT(10X,'NO.',I2/(10X,10('(',I2,')',I4,I2,2X)))
  104 FORMAT(1H1///10X,'<<< NIGERIA SOKOTO AQUIFER MODEL INPUT'
     *       ' DATA >>>'//10X,'NEL   =',I5,7X,'NNO   =',I5/10X,
     *       'ID    =',I5,7X,'NSTEPS=',I5/10X,'NP    =',I5,7X,
     *       'NE    =',I5/10X,'NBAND =',I5,7X,'NWEL  =',I5/10X,
     *       'IP    =',I5,7X,'IHW   =',I5/
     *       10X,'DX    =',F11.5,1X,'DY    =',F11.5/
     *       10X,'DT    =',F11.5/10X,'NBK   =',I5,7X,'NLL   =',I5/)
  105 FORMAT(/10X,'<HEAD-KNOWN-NODE> '/10X,4('NO.',I1,'AQUIFER',I5,2X))
  106 FORMAT(/10X,'NO',I1,'AQUIFER NODE',I5/(10X,5('(',I3,')',F5.1)))
  132 FORMAT(//(10X,6(I2,F8.4)))
  137 FORMAT(//(10X,5(A8,'(',I4,')')))
  144 FORMAT(/10X,I4)
  145 FORMAT(10X,2I4/(10X,10('(',I2,')',F8.0)))
C
      READ(9,107) ((NOP(I,J),J=1,4),I=1,NEL)
      DO 215 I=1,ID
      DO 215 J=1,NEL
  215 LYL(J,I)=1
  138 FORMAT(80I1)
      DO 220 I=1,ID
      READ(2) (T(J,I),J=1,NEL)
      READ(2) (S(J,I),J=1,NEL)
      DO J=1,NEL
```

```
      T(J,I)=T(J,I)*TBAI
      END DO
  220 CONTINUE
  107 FORMAT(32I4)
  108 FORMAT(10F8.0)
  109 FORMAT(10F8.5)
C
      DO 245 I=1,ID
      DO 245 J=1,NNO
  245 LXL(J,I)=1
  140 FORMAT(80I1)
      DO 250 I=1,ID
      READ(2) (KD(J,I),J=1,NNO)
      READ(2) (B(J,I),J=1,NNO)
      DO J=1,NNO
      KD(J,I)=KD(J,I)*KBAI
      END DO
  250 CONTINUE
      READ(4) (H(I,1),I=1,NNO)
      IE=ID+1
      IF(IHIN.EQ.0) THEN
      DO 290 I=2,IE
  290 READ(4) (H(J,I),J=1,NNO)
      ELSE
      DO I=1,IHIN-1
      DO J=2,IE
      READ(29)
      END DO
      END DO
      DO I=2,IE
      READ(29) (H(J,I),J=1,NNO)
      END DO
      END IF
  112 FORMAT(10F8.6)
  113 FORMAT(10F8.6)
  114 FORMAT(10F8.6)
  115 FORMAT(10F8.0)
  116 FORMAT(10F8.2)
  117 FORMAT(20F5.1)
      DO 302 I=1,NNO
  302 ST(I)=0.0
      DO 303 I=1,ID
      DO 303 J=1,NNO
      H0(J,I)=H(J,I+1)
      V(I,J)=0.0
  303 U(I,J)=0.0
C
      RETURN
      END
```

JICA