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INTERACTION OF MULTILAYER AQUIFER SYSTEM WITH STATIC WATER BODY

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PREFACE

Interaction aspects of surface water bodies with groundwater regime are essential features that require in-depth investigation in the light of increased activities related to water resources development and management. Reduction of flow in rivers and declining storage in groundwater reserves may be attributed to mismanagement of surface and ground water resources. Artificial recharge being proposed towards the renewal of dwindling groundwater reserves as well as rejuvenating river flows. This demands availability of good quality water and favourable hydrogeologic conditions. Study of recharge characteristics in complex aquifer systems will be useful not only in the assessment of existing recharge schemes but in the selection of ideal locations for the purpose.

In this study, influence of aquitards on flow in a multilayer aquifer system with a static water source and constant-head boundaries is examined. The effects of position and thickness of aquitards in the medium on the hydraulic potential distribution and flow are subjected to investigation.

The report has been prepared by Mr. Mathew K. Jose and Dr. P.V. Seethapathi of this institute.

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ABSTRACT

Interaction aspects of surface water bodies with groundwater regime are essential features that require in-depth investigation consequent to increased activities of water resources development and management. Nevertheless, comprehensive frame work for the investigation and quantitative results for assessment of interaction characteristics are inadequate. The present report incorporates brief review of relevant literature in the pertaining area. Further, the influence of aquitards in a multilayer aquifer system having static source at the centre and constant-head boundaries is examined. The effects of position as well as thickness of aquitards in the medium on the hydraulic potential distribution and flow are investigated. It has been observed that for a given thickness of the aquitard, its influence is diminishing in the system when the top aquifer to bottom aquifer thickness ratio is increasing. Also, the influence of the aquitard is found insignificant in the system when the aquitard is placed below certain critical depth which is proportional to the aquitard thickness. The average discharge of the bottom aquifer is slightly higher than that of the top aquifer for small ratios of top and bottom aquifer thicknesses. But, the flow tends to become uniform in both the top and bottom aquifers when the influence of aquitards start diminishing at larger ratios of top and bottom aquifer thicknesses. However, generalisation would be possible only after considering a range of scenarios with changed hydraulic and flow parameters.

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1. INTRODUCTION

1.1 General

Surface water bodies like lakes and reservoirs are valuable sources of water for various activities. However the importance of such water bodies are often over looked in water resources planning and development programmes. Precisely, detailed information on interaction between a surface water body and the ground water regime is not readily available. Consequently many problems being encountered in the post-planning period. Such hazards include that of water quality deterioration as well as unfavourable changes in the water budget.

If prior information is made available on the behaviour of, for instance, a lake-groundwater system and the interaction processes, planning procedure may be facilitated to alleviate undesirable effects in future.

1.2 Scope and Objectives

Review of earlier literature brings forth the fact that most of the studies pertaining to surface water groundwater interaction were conducted with reference to specific regions. This implies some difficulty in applying the results obtained thereby to a different situation/region. The knowledge of seepage characteristics from water bodies such as lakes and reservoirs is vital in many context but elaborate/general results are lacking. Hence it may be useful if some studies can be formulated on certain theoretical/ hypothetical situation, which in turn can be applied to similar field conditions. The present study is framed with this objective in view. It is proposed to analyse the ground water flow conditions beneath surrounding a surface water body. A three-Dimensional ground water flow model shall be employed for the purpose. The boundary set up, initial conditions, and the hydrogeologic set up of the hypothetical system are described elsewhere.

It is intended to explore the behaviour of groundwater flow in a multilayered aquifer-aquitard system. Various aspects of flow characteristics would be investigated with respect to positioning of aquitards in the system and variation in physical dimensions of the aquitards. The study aims at evaluating the effect of aquitards (eg. a clay lens), present in an aquifer, on the ground water head distribution and there by on the flow pattern. In the present report, following aspects shall be considered:

(a) Effect of positioning of aquitard of constant thickness in the aquifer, while keeping the physical dimensions of the aquifer and water body constant.

(b) The distribution of heads (potentials) with respect to distance from the water body under steady-state conditions.

(c) The discharge characteristics in the top unconfined aquifer and that in the confined bottom aquifer.

(d) The discharge and potential behaviour in relation to changing thicknesses of the aquitard.

Relationships or type curves involving hydraulic potentials, flow and aquifer characteristics in terms of dimensionless quantities would enable application of results to appropriate field situations. By considering various aspects of flow in water body-aquifer-aquitard system with a range of boundary conditions further insight into groundwater interaction characteristics may be obtained. Variation in hydraulic parameters to relative to that of the aquifer material, change in boundary conditions, number of layers present and their hydraulic properties, change in physical dimensions of the aquifer as well as the water body including head-causing flow shall be subjected to investigation later on.

2. REVIEW OF LITERATURE

Following is a brief review of relevant literature pertaining to interaction studies. Of which considerable contributions are with special reference to lakes/ reservoirs in specific geo-climatic conditions only.

Groundwater flow patterns around lakes/ surface water bodies were studied by Mc Bride and Pfannkuch (1975), Winter (1976,1981,1983 & 1986). Winter (1981) stated that in most of the studies the groundwater components had been estimated as residuals in the water budget. However this type of procedure may lead to erroneous quantification of groundwater as inherent measurement/ estimation errors already exist in other components, such as precipitation and evaporation, of the water budget.

Mc Bride and Pfannkuch (1975) developed two dimensional digital model to examine the distribution of seepage below and through lake bottom sediments. They tested the model on Lake Sallie, Minnesota and found nearly all seepage flowing into a lake is concentrated in a narrow zone near the shore. An exponential decrease in seepage away from the shoreline is noticed.

Winter (1976) employed numerical simulation technique to study interaction of lakes and groundwater. His study mainly concerned with lakes encircled by watertable mounds that are at a higher altitude than lake level. It is shown that, if the divide (line separating local from regional groundwater flow systems) is continuous, then, there exist a point along it at which the head is a minimum and this point of minimum head is always greater than the lake level. Therefore in such a situation there can be no movement of lake water through the bed to the groundwater system. On the other hand, if the divide is not continuous, the lake loses water through part of its bed. His study brought out factors that influence the position, shape and continuity of the flow system divide beneath lakes. The factors identified are height of water table on the downslope side of the lake relative to lake level, position and hydraulic conductivity of aquifers within the groundwater reservoir, ratio of horizontal to vertical hydraulic conductivity of the aquifer and lake depth. However, the general applicability of those results may be examined before using at different situations, for this study was mostly pertaining to lakes in glacial terrane conditions only.

Marsily et.al. (1978) investigated possibility of modelling large multilayered aquifer systems.

Flow mechanisms in large sedimentary basin with a distinction between the behaviour of aquifers and aquitards were given. Finite difference technique was used for solving flow equations and an application of the method in the Sahara region is also detailed.

Ruston and Tomlinson (1979) studied leakage between aquifers and rivers using an idealised one dimensional problem. Leakage is represented by a linear coefficient, a non-linear coefficient and combination of the two. It has been shown that baseflow recessions are effectively independent of the magnitude of the linear leakage coefficient.

Born et al. (1979) compiled hydrogeologic data for numerous lakes in North America and presented a classification framework for lakes based on hydrogeologic consideration. The hydrogeologic factors used for the assessment of lake environments were: (a) the relative magnitude of groundwater in the total water budget of a lake (regime dominance); (b) description of the rate aspects of surface and ground water movement through a lake system (system efficiency) and; (c) position within a groundwater flow system. Three major types of lakes were identified based on their flow characteristics; viz., recharge lakes, discharge lakes and flow-through lakes. Lakes situated in groundwater recharge areas can contribute to the groundwater through lake bottom (recharge lakes). Lakes in groundwater discharge area gain groundwater through the lake perimeter and partially through the bottom (discharge lakes). In areas of lateral groundwater flow, lakes lose to the groundwater on one side and gain groundwater on the other side (flow-through lakes).

Munter (1981) modeled transient ground water flow near actual lakes by fixing the position of the water table and specifying it as a flux boundary. This approach required the assumption that the flux across the water table be known. However, without a thorough understanding of the ground water recharge and discharge processes, one cannot be confident of assumed fluxes.

Lafe et al (1981) reported solution to aquifers having leaky, layered, confined or unconfined situations using boundary integral equation method. However, the system is simplified using Dupuit assumption thereby limiting the applicability of the solution for complex aquifers exists in nature.

Winter (1981) made a detailed investigations on uncertainties in estimating water balance of lakes. He pointed out that estimating ground water components of the budget as residuals, is erroneous due to measurement errors in precipitation, evaporation, overland flow and stream discharges. Also, regionalisation errors result from estimating quantities in time-space continuum from point data.

Winter (1983) studied the interaction of lakes with variably saturated porous media. It was found that transient groundwater flow systems have significant impact on contiguous surface water by alternately causing seepage to and seepage from the surface water. The findings indicated that wells and groundwater quality sampling sites needs to be carefully located to define accurately water table configuration, groundwater recharge, direction of seepage through the beds of surface water bodies, and complex geochemical processes related to changing directions of groundwater flow.

Numerical simulation analysis was made for variations in the coefficient of anisotropy for several lake-groundwater settings having different geometric configurations (Winter and Pfannkuch, 1984) . Overall geometry and anisotropy of the media are two interrelated geometric factors affecting flow. The analyses reveal that, for a given geometric setting, as the anisotropy decreases seepage from a lake decreases and depth of the local groundwater system associated with the lake increases. Also, it is mentioned that as thickness of groundwater system decreases, relative depth of the local flow system increases and seepage from the lake decreases. This investigation demonstrates the use of groundwater flow models in interaction studies.

Pfannkuch and Winter (1984) studied the effect of anisotropy and groundwater system geometry on seepage through lake beds. Distribution of seepage through lake beds is controlled partly by geometric configuration of lake bed and of groundwater system interacting with the lake. They used electric-analogue models to study these effects. A width ratio, the ratio of half the lake width to thickness of groundwater system is used as the principal geometric characteristic in the study. Three width ratio groups were identified with distinct flow patterns. The analysis was with extremely simplified boundary and flow-field conditions. Also, it was assumed that the other half of the lake and groundwater system as mirror images.

Winter (1986) analysed water level fluctuations in several lakes and observation wells around in the sand-hills of Nebraska and reported that water-table configuration in the area varies depending upon the configuration of the topography of the dunes. The effects of groundwater recharge on water table configuration and the effect of changes in water table on direction of seepage through lake beds were also investigated. For a hummocky dune, ground water recharge is focused at topographic lows causing formation of water table mounds which prevent ground water movement from lakes at higher elevations to adjacent lower ones. If a dune ridge is sharp water table troughs are formed between lakes. Lakes aligned parallel to the principal direction of regional ground water movement, have seepage from higher lakes towards lower lakes.

Townley and Davidson (1988) investigated lake-aquifer interaction to develop simple relationships between easily measurable geometrical and aquifer parameters and the bulk behaviour of the flow system using two dimensional geometries in plan and vertical section. Boundary integral approach is used to solve the resulting problems. The size of an upstream capture zone, in which all ground water flow eventually passes through the body of the lake, is defined in terms of the size of the lake, inter-lake spacing, aquifer saturated thickness, an anisotropy ratio and the ratio of downstream to upstream hydraulic gradients.

Yates (1988) reported an analytical solutions to saturated flow in a finite stratified aquifer. However, the solution is of limited use only as the system consists only three layers and horizontal flow is assumed everywhere.

Fitts (1991) attempted modelling three dimensional flow about ellipsoidal inhomogeneities in porous medium. Analytic functions are superimposed to model three-dimensional steady groundwater flow in regions containing one or more ellipsoidal inhomogeneities. Such functions are solutions of Laplace equation and are implemented so as to provide continuity across the entire boundary of inhomogeneities. However, application of the method to a complex aquifer system containing many inhomogeneities result in the problem of finding solution to huge number of simultaneous linear equations.

Nield et al (1994) used a numerical model to examine groundwater flow in vertical section near surface water bodies. Different flow regimes were identified with their characteristics controlled by regional water table gradients, recharge to the aquifer, water body length, aquifer anisotropy, and to hydraulic resistance of the bottom sediments. The study indicates that increasing anisotropy or sediment resistance and decreasing the length of a water body relative to aquifer thickness have similar effects on flow geometry, the main effect being an increasing tendency for stagnation points to form in the interior of the aquifer. Flow through behaviour becomes more prevalent with decreasing anisotropy and sediment resistance and increasing water body length.

A quasi-three-dimensional numerical model that incorporated groundwater-surface water interaction and boundary flows from a larger regional model was used by Pucci Jr. and Pope (1995) to represent the Potomac-Raritan -Magothy aquifer system in USA in order to simulate developmental effects on water resources. Significant differences in simulated groundwater-surface water interactions between pre-development and developed system are reported covering redistribution of recharge and discharge areas as well as reduced groundwater discharge to streams. This study demonstrates the utility of assessing groundwater surface water interaction in a regional hydrogeologic system by simulation responses to development.

It may be observed that various studies conducted are more or less unique in its approach and are confined to specific regions of interest. Therefore, generalisation of any sort may not be appropriate.

3. PROBLEM FORMULATION

The objective of the study is to examine the influence caused by the presence of an aquitard (leaky layer) in an aquifer with specified boundaries. A surface water body is situated at the centre of the system. Real life situation need not be conformed with any well defined shape or boundaries as depicted in the hypothetical settings. In order to arrive at general conclusions on the behaviour and characteristics of the system, a simplified arrangement is used. However, similar field situations may be approximated to a certain degree to conform with the idealised set up without lose of generality.

Attempts were made earlier to develop type curves for the assessment of recharge and seepage for hypothetical lake in an isotropic aquifer medium (Singh and Seethapathi, 1990). However, the aquifer under investigation was considered homogeneous and no layered/ multi aquifer systems were studied. The attempt here is to stratify the homogeneous system with the introduction of leaky layers.

The plan of the layered aquifer system under investigation is given in (Fig.1). The surface water body is located at the centre of the square shaped plan. The sides of the water body are 300m each. The depth of the aquifer is assumed to be 100m at the centre of the water body and the total depth to an impermeable bed is 103m. (Fig.2). The boundaries of the aquifer system extends to a distance of 3600m in X and Y directions from the centre of the surface water body . Along the Y-direction the boundaries of the aquifer are fully penetrating constant head rivers. Along the X-direction no-flow boundaries are postulated to restrict the flow mainly to two dimensional.

3.1 Spatial Discretisation

To facilitate the finite difference application of the flow equations, the system is discretized into rectangular grids consisting of 32 rows x 32 columns in plan. Variable grid spacing in logarithmic scale, progressing from the centre to the boundaries, is employed so that more detailed information from finer grids will be available in and around the surface water body while limiting the total number of grids. The water body is discretized into 25 grids of equal sizes. The total depth of the aquifer is divided into 9 layers with varying thicknesses. The two leaky layers separate the aquifer into unconfined and confined layers. The discretised system consists of more than 9000 cell-blocks.

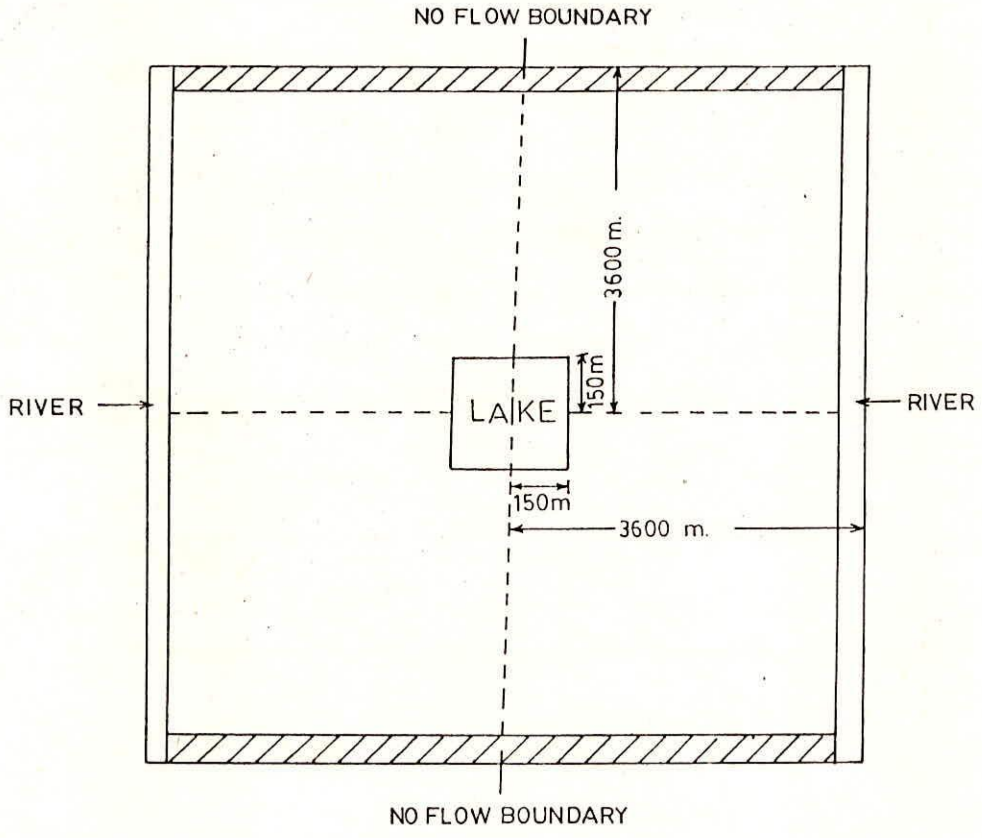

FIG. 1 PLAN VIEW OF THE STATIC WATER BODY-AQUIFER SYSTEM

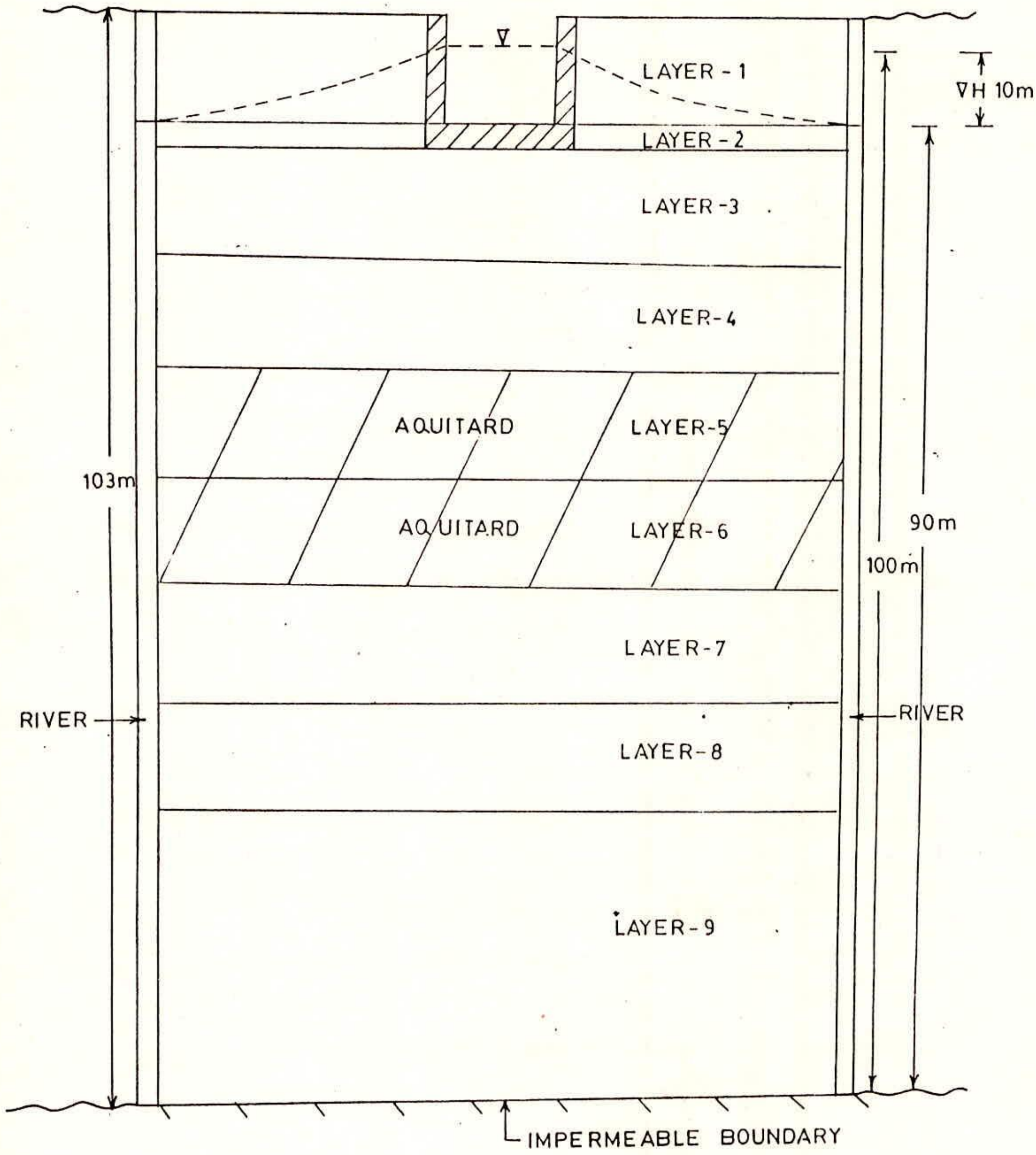

FIG. 2 CROSS SECTION OF THE HYPOTHETICAL LAKE-AQUIFER-AQUITARD SYSTEM

The ratio of vertical hydraulic conductivity to that of the horizontal component is assumed unity. Also each layer is assumed isotropic and homogeneous in itself. That is, the variation in aquifer parameters is between different layers only. The hydraulic conductivity value for the aquifer portion of the system is 3E-4 m/s. The specific yield for the unconfined aquifer is taken to be 0.15 where as the storage coefficient for the confined layers is 1E-5. Similarly for the aquitard portion the hydraulic conductivity value is 3E-6 m/s and storage coefficient is 1E-3. The sides and bottom of the lake are assumed to be having a layer of clay sediments having the properties of the aquitard.

3.2 Discretization in time

The total period of simulation (stress period) is chosen to be 500 days for steady state situation, after verification. 50 time steps consisting of 10 days each are used in the simulation. The distribution of head and volumetric details have been obtained at the end of selected time steps and at the end of the simulation period for further analysis. The total outflow (the volumetric quantity of water discharged from the system during the stress period) in any simulation is found to be linearly related with simulation time (Fig.3). The percentage changes in consecutive outflows for various time steps were computed (Fig.4).

It may be noticed that change in outflow tends asymptotically to zero as the length of the stress period increases and in the vicinity of 500 days it is negligibly small.
The absolute hydraulic potentials for various sections in the medium tend to stabilise to a steady state as the stress period approaches 500 days (Fig.5). Thus, a stress period of 500 days is found to be sufficient for attaining steady state condition with the present set up designed. Before proceeding with simulations, correctness of model formulation and validity of results have been checked with known situations.

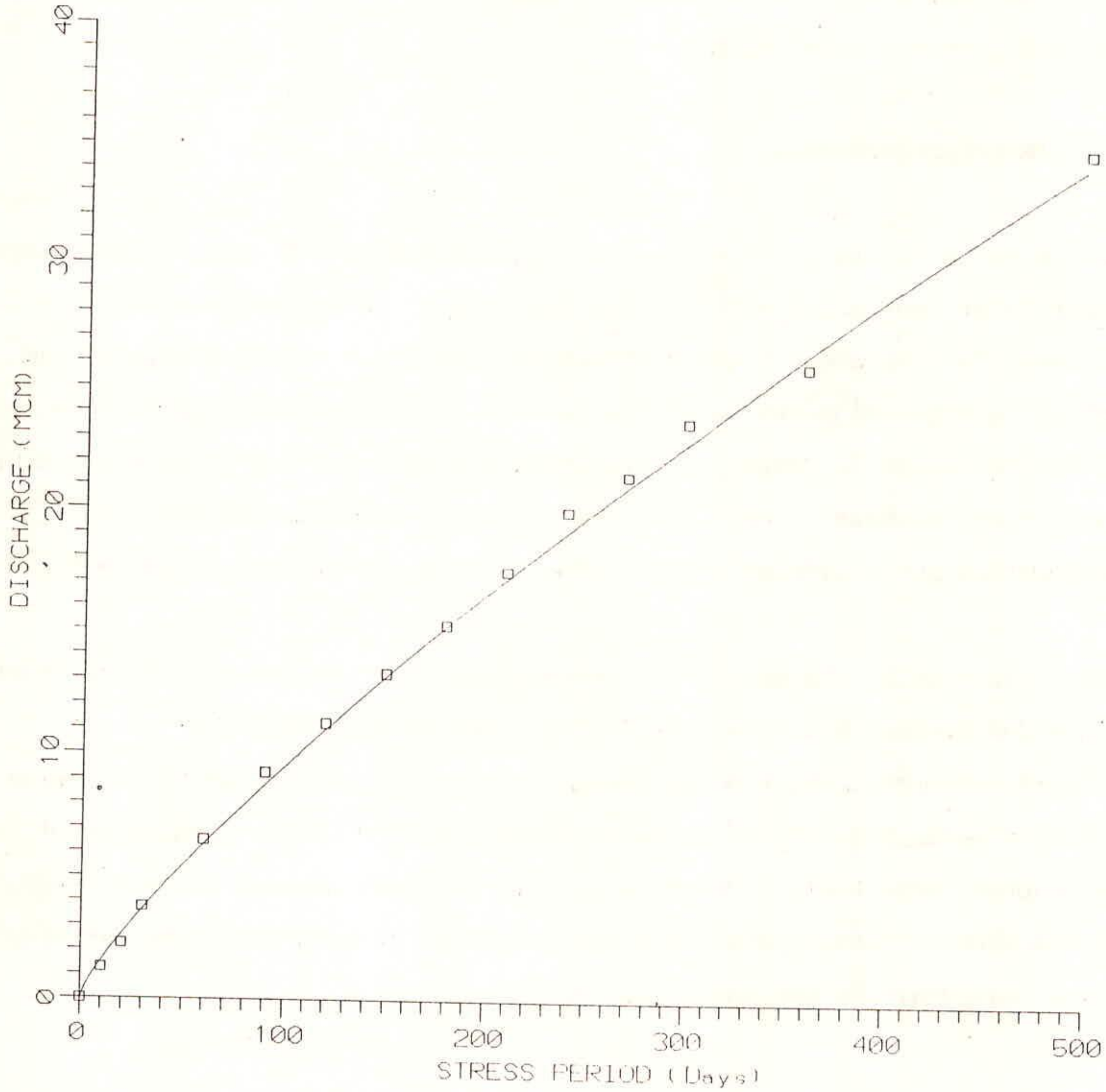

FIG 3 TIME STEP Vs OUTFLOW FROM THE SYSTEM

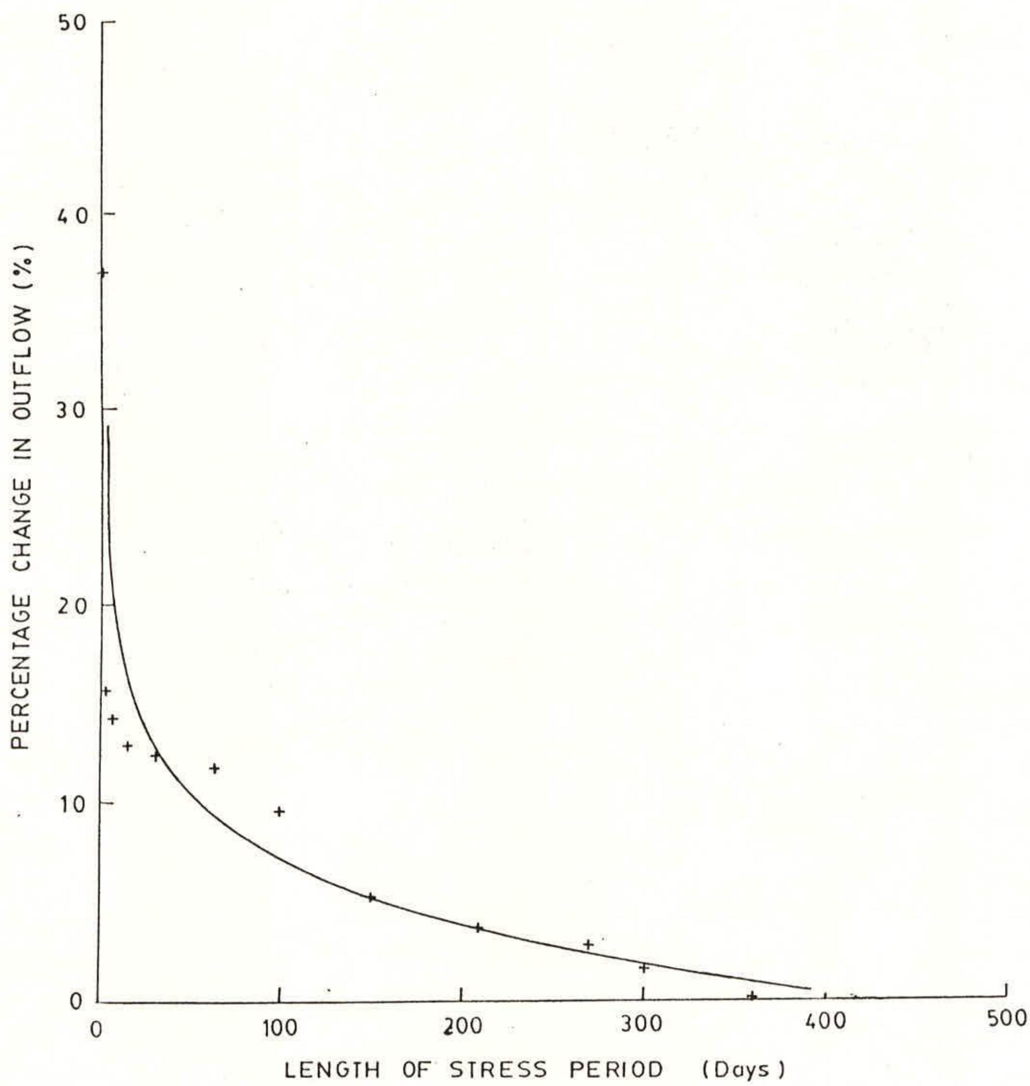

FIG.4 STEADY STATE SITUATION WITH RESPECT TO LENGTH OF STRESS PERIOD

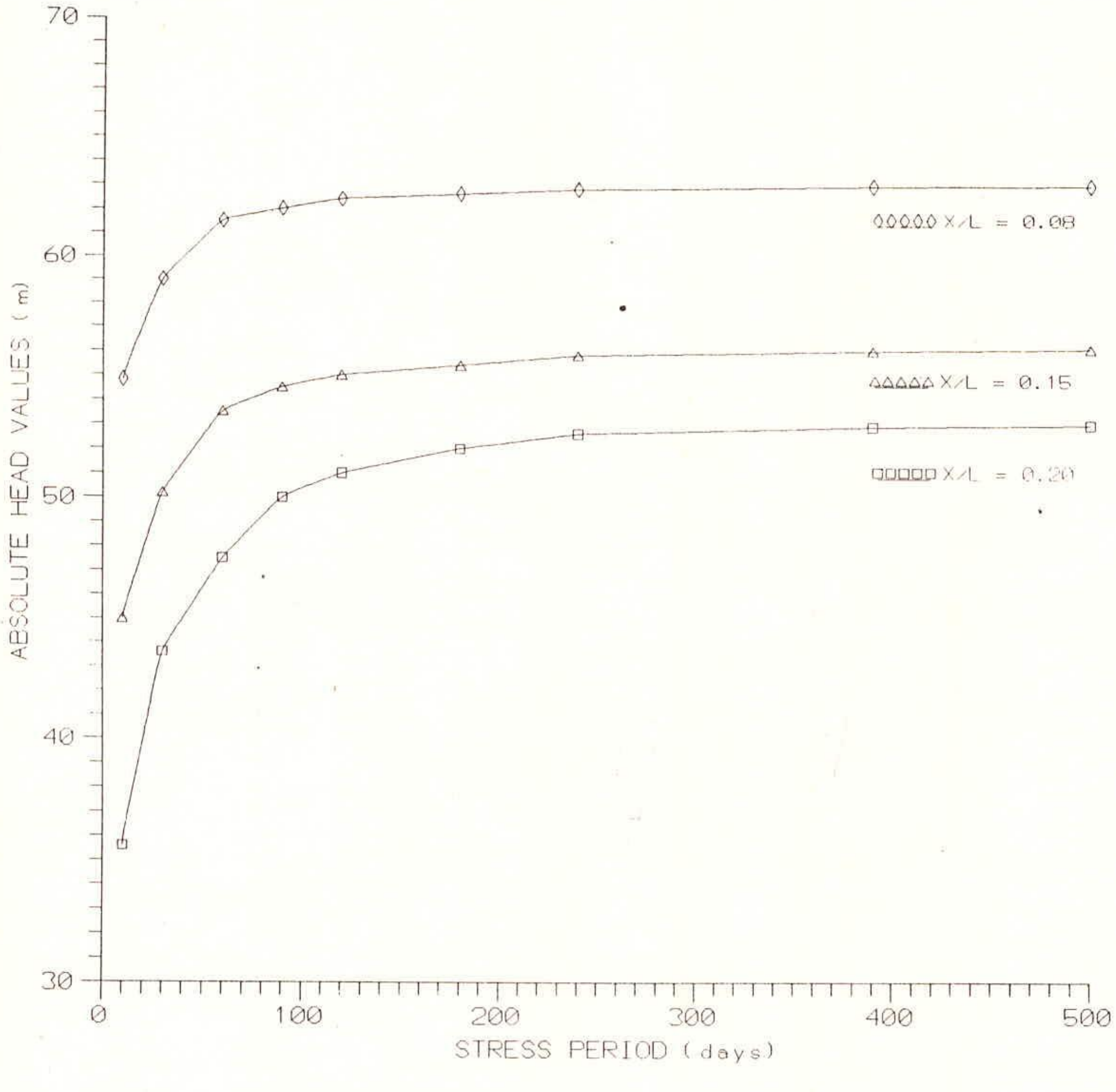

FIG.5 VARIATION OF ABSOLUTE HEAD WITH STRESS PERIOD AT DIFFERENT SECTIONS OF THE AQUIFER SYSTEM

4. METHODOLOGY

A modular three dimensional finite difference groundwater flow model originally developed at the U.S. Geological Survey, USA (Mc Donald and Harbaugh, 1984) is employed for studying the flow pattern. Dimensions of the matrix arrays are augmented to cope with the total number of grid points in the system.

4.1 Governing equations

The three dimensional unsteady groundwater flow through heterogeneous and anisotropic porous earth material is given by the partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where,

K_{xx},K_{yy},K_{zz} : hydraulic conductivities along the major axes

h : potentiometric head

W : volumetric flux per unit volume and represents sources and or sinks

S_s : the specific storage of the aquifer

t : time

In general, S_s, K_{xx}, K_{yy} and K_{zz} are functions of space, for example: $K_{xx} = K(x,y,z)$, whereas h and W are functions of space and time (eg: $h = h(x,y,z,t)$). Thus, the above equation describes groundwater flow under non-equilibrium conditions in a heterogenous and anisotropic medium. Hence this equation together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions, constitutes a mathematical model of ground water flow.

Generally analytical solutions of the equation referred above are rarely possible. So various numerical methods may be used to arrive at approximate solutions. The well known finite difference method is one such approach. With this method, the continuous system is replaced by a system of simultaneous linear algebraic difference equations and their solution yields values of head at specific points and time. These constitute an approximation to the time varying head distribution that would be given by an analytical solution of the flow equation.

4.2 Model description

Development of the groundwater flow equation in finite difference form follows from the application of the continuity equation: the sum of all flows into and out of a cell must be equal to the rate of change in storage within the cell. The finite difference approximation for any cell (i,j,k) in the grid may be obtained as:

$$
\begin{aligned}
&CR_{i,j-½,k}\,(h_{i,j-1,k} - h_{i,j,k}) + CR_{i,j+½,k}\,(h_{i,j+1,k} - h_{i,j,k}) \\
&+ CC_{i-½,j,k}\,(h_{i-1,j,k} - h_{i,j,k}) + CC_{i+½,j,k}\,(h_{i+1,j,k} - h_{i,j,k}) \\
&+ CV_{i,j,k-½}\,(h_{i,j,k-1} - h_{i,j,k}) + CV_{i,j,k+½}\,(h_{i,j,k+1} - h_{i,j,k}) \\
&+ P_{i,j,k}\,h_{i,j,k} + Q_{i,j,k} = SS_{i,j,k}(\Delta r_j \Delta c_i \Delta v_k)\Delta h_{i,j,k}\,/\Delta t
\end{aligned}
$$

where,

$CR_{i,j-½,k}$	: the conductance in row i and layer k between nodes i,j-1, k and i,j,k
$CC_{i-½,j,k}$	: the conductance in column j and layer k between modes i-1,j,k and i,j,k.
h,j,k	: the head in cell i,j,k
$CV_{i,j,k-½}$	: the conductance in row i and column j between modes i,j,k-1 and i,j,k
$P_{i,j,k}$	: certain constant for cell i,j,k
$SS_{i,j,k}$	: specific storage of cell i,j,k.
$Q_{i,j,k}$	: flow rate into cell i,j,k.
$\Delta r_j \Delta c_i \Delta v_k$	: volume of cell i,j,k is recent in time.
Δt	: increment in time

The above equation can be rewritten in backward-difference form by specifying flow terms at t_m, end of the time interval, and approximating the time derivative of head over the interval t_{m-1} to t_m as:

$$
\begin{aligned}
&CR_{i,j-½,k}(h^m_{i,j-1,k} - h^m_{i,j,k}) + CR_{i,j+½,k}(h^m_{i,j+1,k} - h^m_{i,j,k}) \\
&+ CC_{i-½,j,k}(h^m_{i-1,j,k} - h^m_{i,j,k}) + CC_{i+½,j,k}(h^m_{i+1,j,k} - h^m_{i,j,k}) \\
&+ CV_{i,j,k-½}(h^m_{i,j,k-1} - h^m_{i,j,k}) + CV_{i,j,k+½}(h^m_{i,j,k+1} - h^m_{i,j,k}) \\
&+ P_{i,j,k}h^m_{i,j,k-1} + Q_{i,j,k} \\
&= SS_{i,j,k}(\Delta r_j \Delta c_i \Delta v_k)\ \{ (h^m_{i,j,k} - h^{m-1}_{i,j,k}) \,/\, (t_m - t_{m-1}) \}
\end{aligned}
$$

If an equation of this type is formulated for each of the 'n' cells in the gridded system, then we are left with a system of 'n' equations in 'n' unknowns and the set of equations can be solved for obtaining the unknown head values for each of the cells.

In the finite difference method, the continuous system described by the governing equation is replaced by a finite set of discrete points in space and time and the partial derivatives are replaced by differences between functional values at these points. This requires discretization of the aquifer system into grids forming rows, columns and layers. To conform with computer array conventions an i, j, k, coordinate system is used where i is the row index j is the column index and k is the layer index. Nodes represent cell within which the hydraulic properties are constant. Hence, any value associated with a node is distributed over the extent of the cell. The width of the cells along row is designated as Δr_j for the j^{th} column and that along the column is Δc_i for the i^{th} row. Now the volume of the cell located at (i,j,k) is $\Delta r_j \Delta c_i \Delta v_k$, where Δv_k is the thickness of the layer k.

The block-centred formulation is used for defining the configuration of cells for the present study. The cells are formed by parallel lines and the mid-points are the nodes. For each block, the hydraulic properties are uniform over the extent of a cell.

4.3 Boundary Conditions

In the discretised aquifer system, the number of equations is equal to the number of *variable-head cells*. Variable-head cells are those in which head may vary with time. Cells that are not variable-head cells may be either *constant head* or *no-flow cells*. Constant head cells are those in which head remains constant with time and noflow cells are those to which there is no flow from adjacent cells. The type of boundaries that may be imposed in the model include, constant head, no-flow, constant-flow and head-dependent flow.

4.4 Solution procedure

An iterative method starting with an initial trial solution is used. An interim solution (approximate) is obtained and it becomes the new trial solution and the procedure is repeated until the *closure criterion* is met. The iterative solution package known as the strongly Implicit procedure (SIP) is adopted. The closure criteria is kept to the order of magnitude of 10^{-5}.

5. ANALYSIS AND DISCUSSION

For the hypothetical problem described earlier, simulation of flow from the source (the water body) to the Sink(the constant head boundaries) is carried out with different parameter values and set up. The three dimensional finite difference groundwater flow model (MODFLOW) is used.

The following general assumptions have been imposed in the formulation of the study:

(a) The layers are continuous and parallel to the ground surface

(b) The hydraulic parameters vary from layer to layer only; that is, any single layer is homogeneous and isotropic in its own worth

(c) Uniform horizontal and vertical hydraulic conductivities for individual layers

(d) Impermeable lower boundary at finite depth

(e) Steady state flow situation

(f) Flow is predominantly toward the fully penetrating constant-head river boundaries

(g) No flow across the boundaries parallel to the X- axis

(h) Head (causing flow) in the static water body remains constant throughout the simulation

(i) Uniform seepage from the water body

(j) No change in the density of water in the region

The head difference between the water body and the constant head boundary is kept 10m initially. The total depth of the aquifer system is 100m at the centre consisting of nine layers of which two are aquitards. The total surface area in plan is about 600 times that of the waterbody. The ratio of any lateral side of the plan area to that of the water body is about 25. Types of various layers, thicknesses, hydraulic conductivities and storage coefficients for the hypothetical aquifer-aquitard system are given in table 1.

The arbitrary choice of hydraulic conductivity as well as storage coefficient values is in conformity with general considerations. Hydraulic conductivity of aquitards and that of the aquifer material differs by two orders of magnitude. The specific yield for the unconfined layers above aquitards is taken to be 15 percent. Storage coefficients for the aquitards and confined aquifers are also within acceptable ranges. The horizontal and vertical hydraulic conductivities have been assumed to be uniform for corresponding layers.

Table 1 Particulars of various layers in the aquifer-aquitard system

Layer Number	Layer type	Layer thickness (m)	Hydraulic conductivity (m/s)	Storage coefficient
1	Aquifer	10	3×10^{-4}	0.15
2	Aquifer	3	3×10^{-4}	0.15
3	Aquifer	10	3×10^{-4}	0.15
4	Aquifer	10	3×10^{-4}	0.15
5	Aquitard	10	3×10^{-6}	1×10^{-3}
6	Aquitard	10	3×10^{-6}	1×10^{-3}
7	Aquifer	10	3×10^{-4}	1×10^{-5}
8	Aquifer	10	3×10^{-4}	1×10^{-5}
9	Aquifer	30	3×10^{-4}	1×10^{-5}

The hydraulic potentials are obtained for different layers at steady state situation and discharges are computed. The flow is mostly two dimensional because of no flow boundaries parallel to the X-axis.

Following dimensionless parameters have been defined prior to analysis:

(a) *Distance ratio (X/L)*: Distance from the centre of the static water body to any arbitrary point in the X-direction (X) normalised with respect to half width (L) of the system.

(b) *Aquitard head ratio (ATHR)*: Ratio of hydraulic potential in top unconfined aquifer to that in the aquitards.

(c) *Aquifer head ratio (AFHR)*: Ratio of hydraulic potential in top unconfined aquifer to that in bottom confined aquifer.

(d) *Discharge ratio (DISR)*: ratio of average discharge per unit thickness of top aquifer to that of bottom aquifer/ aquitard.

(e) *Aquitard depth ratio (ATDR)*: ratio of depth of top surface of the aquitard to thickness of the aquitard.

(f) *Aquifer thickness ratio (AFTR)*: ratio of thickness of top aquifer to thickness of bottom aquifer.

The choice of above ratios, viz; X/L, ATHR, AFHR, DISR, ATDR and AFTR, is found to be useful in the foregoing analysis.

Table 2 Aquitard depth ratios and aquifer thickness ratios for various cases

Cases	Aquitard depth-ratios	Aquifer thickness ratios
1	1.20	0.40
2	1.40	0.50
3	1.65	0.70
4	1.90	0.80
5	2.15	1.10
6	2.40	1.40
7	2.65	1.80
8	2.90	2.30
9	3.10	3.00

Simulations are carried out with the aquitards positioned at various depths. This is facilitated by changing the thicknesses of layers in the top aquifer and/or thicknesses of layers in the bottom aquifer while keeping the total depth of the system unaltered. The effect of thicknesses of aquitards on the flow was also investigated. While changing the aquitard thicknesses, the ratio of the depth of top surface of the aquitard to the thickness of the aquitard has been retained constant. Various cases have been examined to ascertain the potential and discharge characteristics (Table-3).

It has been observed that the influence of boundaries diminish beyond X/L = 0.5 and thereafter no significant changes observed thereafter between values of consecutive cell blocks. Thus, the choice of position of boundaries with respect to the source can be considered essentially at infinite distances from the source so that the flow regime is unaffected by any boundary effects.

The hydraulic heads in different layers for various columns in the discretized aquifer system have been obtained with the set up described earlier for different cases. Fig.6 depicts the variation of average heads in the top unconfined aquifer and bottom confined aquifer due to the influence of constant thickness aquitard placed at different depths in the system. The ratio of average potentials in the top and bottom aquifers are plotted against the aquitard depth

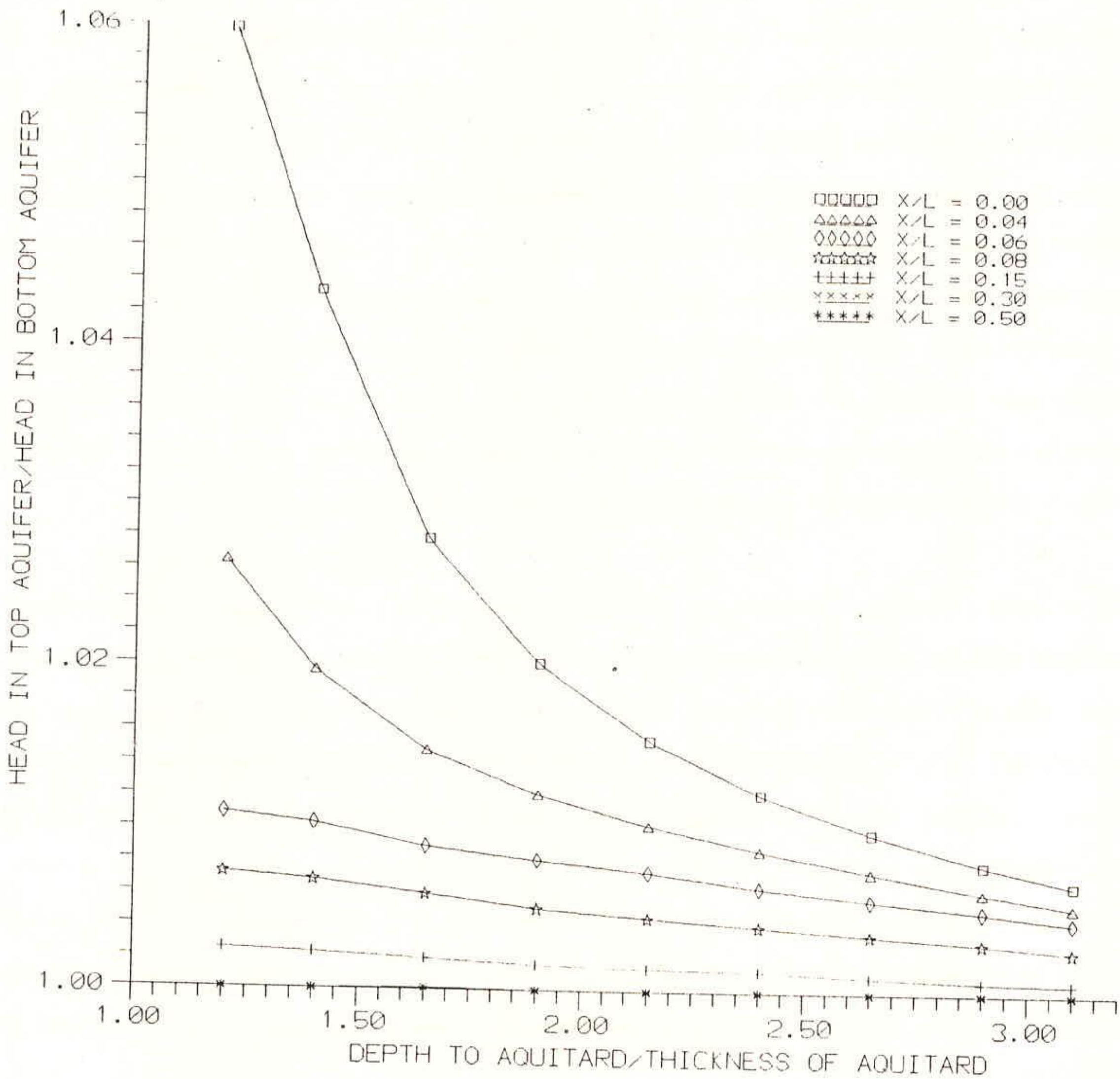

FIG.6 VARIATION OF RATIO OF HEADS IN THE TOP AND BOTTOM AQUIFERS WITH POSITIONING OF AQUITARD AT DIFFERENT DEPTHS OF THE SYSTEM

ratios (ATDR) to see the influence of positioning of aquitards in the system. The ratio of heads have also been plotted for various X/L ratios reflecting the behaviour with respect to distance from the centre of the system.

It may be observed that as the aquitard depth ratio increases the potential in the top aquifer and that in the one below the aquitards steadily approaching the same value. Beyond a depth ratio equal to 3.0 the difference between those head ratios are negligibly small. Since the aquitard thickness being kept constant, with increasing aquitard depth ratios (ATDR), the aquitards are placed at deeper depths. In other words, when the aquitards are nearer to the source they tend to transmit flow due to pressure build up in the top aquifer compared to the bottom aquifer. At depth ratios higher than 3.0 the influence of aquitards are diminishing apparently and no vertical flow takes place as the potentials in all the layers are approaching a uniform steady state value. The maximum differences in the head values for all aquitard depth ratios (ATDR) are recorded for various X/L ratios (Fig.8). Further, difference in potentials in top aquifer and bottom aquifer are waning as one moves away from the centre (X/L = 0) and eventually becomes insignificant beyond X/L = 0.5 (Fig.8).

The aforesaid behaviour has been verified by examining the ratio of heads in the top aquifer and aquitards for several depth ratios (Fig.7). A similar pattern, as in the previous case, has been noticed. Head ratios approach unity beyond aquitard depth ratio, ATDR = 3 and also beyond X/L = 0.5. Nonetheless, there is a marked reduction in the magnitude of the head ratios signifying higher potentials in the aquitard compared to the bottom aquifer. Accordingly, the hydraulic potential distribution in the vertical plane is one which is gradually decreasing from top aquifer to bottom aquifer through aquitards as well as from centre to boundaries when the aquitards are nearer to the source. This hydraulic potential difference results in a vertical gradient sustaining flow toward the bottom aquifer through the aquitards.

Precisely, the hydraulic potentials tend to be uniform everywhere in the aquifer-aquitard system for aquitard depth ratios (ATDR) and distance ratios (X/L) higher than certain critical values thereby nullifying the influence of aquitards present.

The ratio of heads in the top aquifer to the bottom aquifer and the same for the top aquifer to the aquitard have been traced [Fig.9(A) - 9(E)] against X/L ratios for different aquifer thickness ratios (AFTR). It may be noticed that the corresponding head ratios for the top

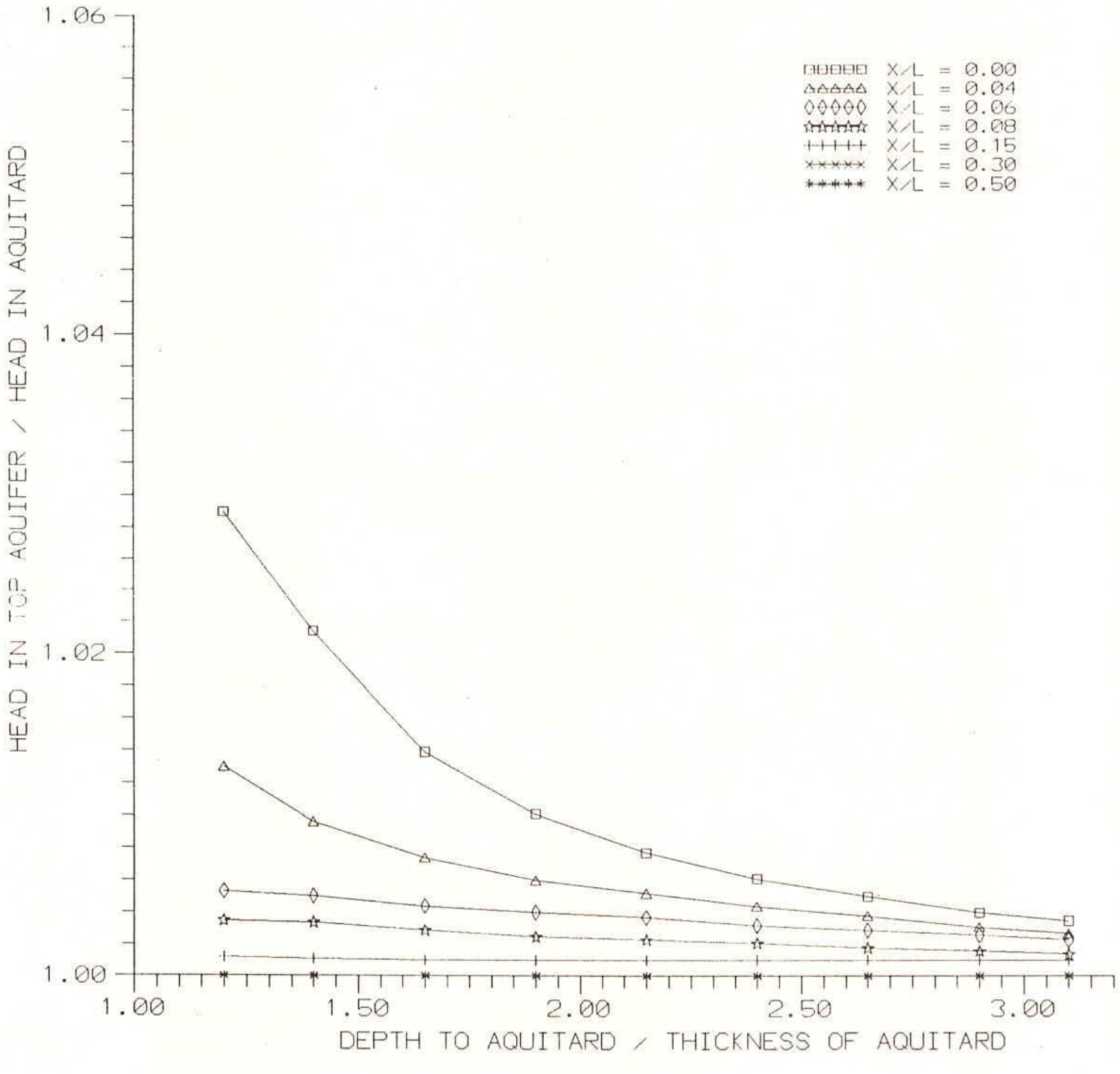

FIG.7 VARIATION OF RATIO OF HEADS IN THE TOP AQUIFER AND AQUITARD WITH POSITIONING OF AQUITARD AT DIFFERENT DEPTHS

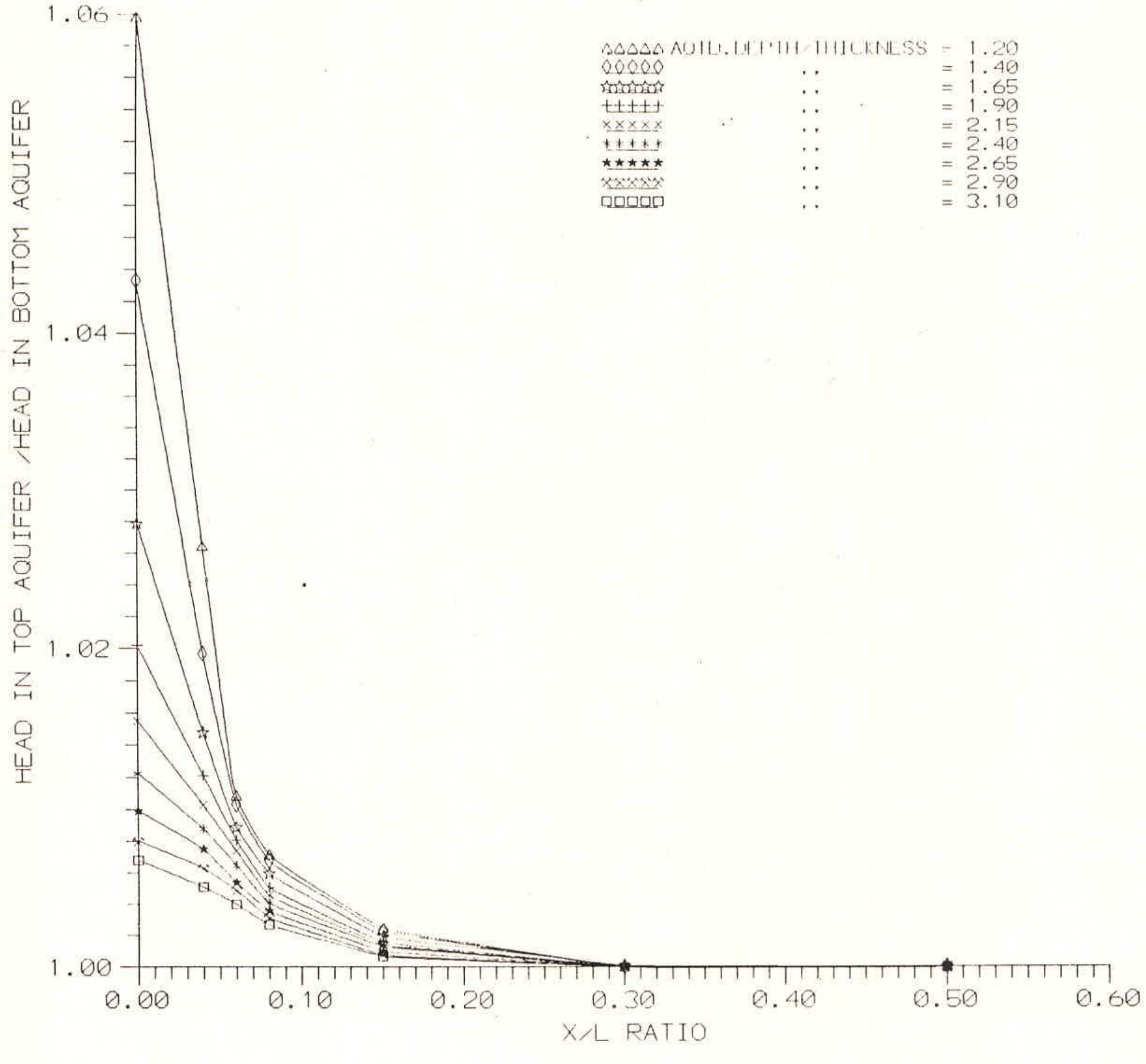

FIG.8 RATIO OF HEADS IN TOP AND BOTTOM AQUIFERS Vs. DISTANCE FROM CENTRE OF THE SYSTEM FOR VARIOUS AQUITARD DEPTH / THICKNESS RATIOS

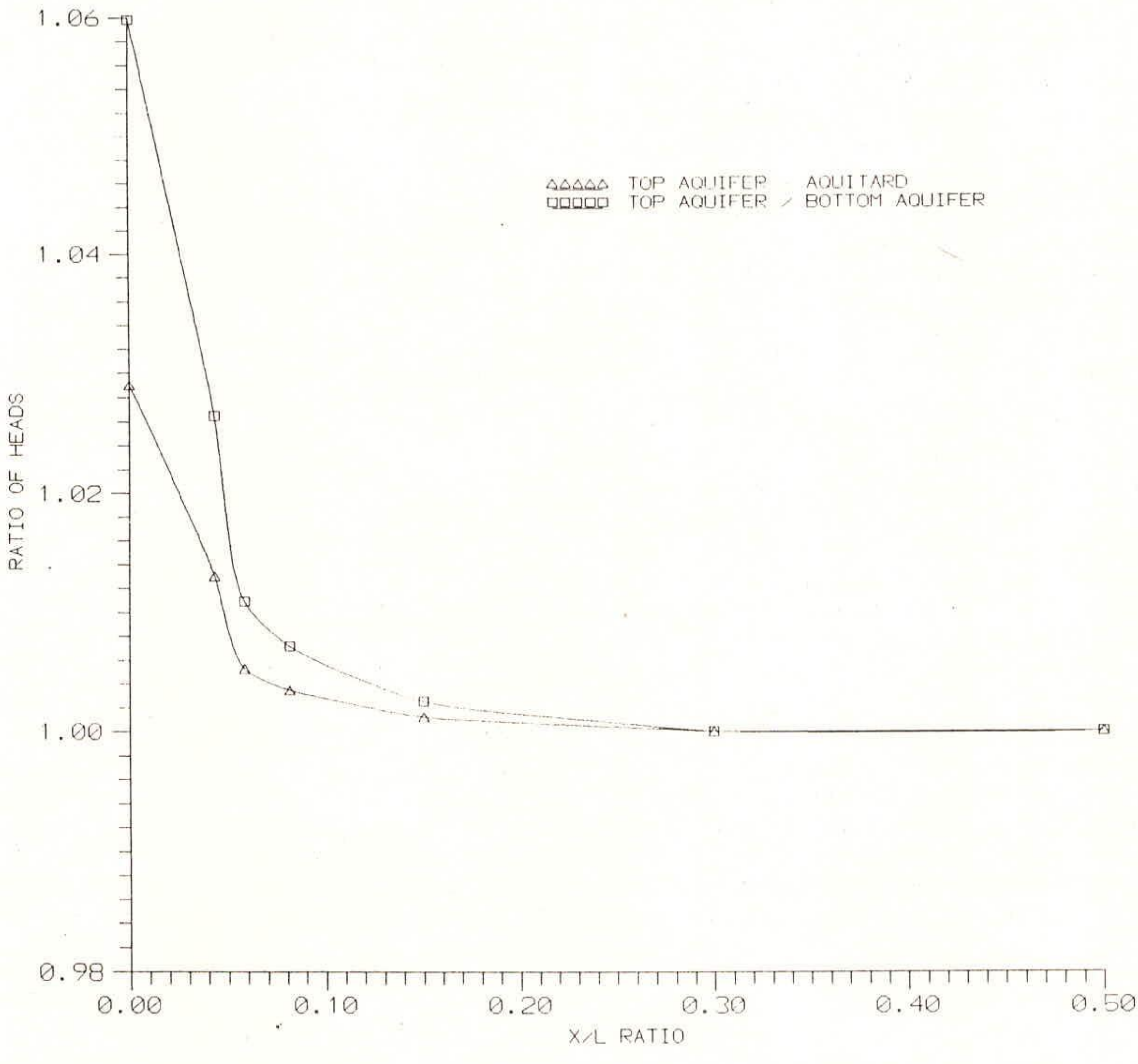

FIG.9(A) RATIO OF HEADS IN TOP AQUIFER TO BOTTOM AQUIFER AND TO AQUITARD FOR THICKNESS RATIO OF TOP AQUIFER TO BOTTOM AQUIFER = 0.40

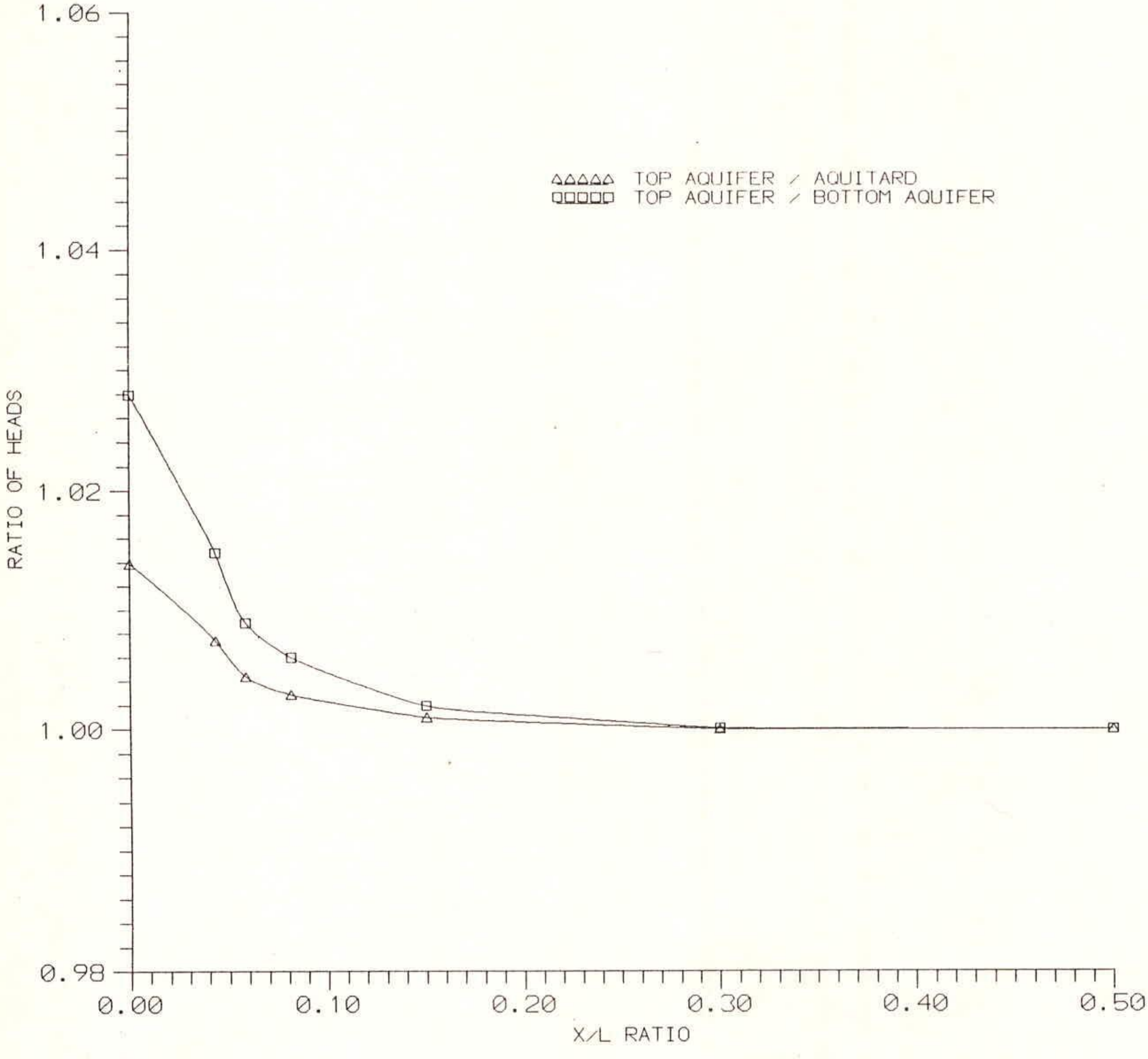

FIG.9 (B) RATIO OF HEADS IN TOP AQUIFER TO BOTTOM AQUIFER AND TO AQUITARD FOR THICKNESS RATIO OF TOP AQUIFER TO BOTTOM AQUIFER = 0.70

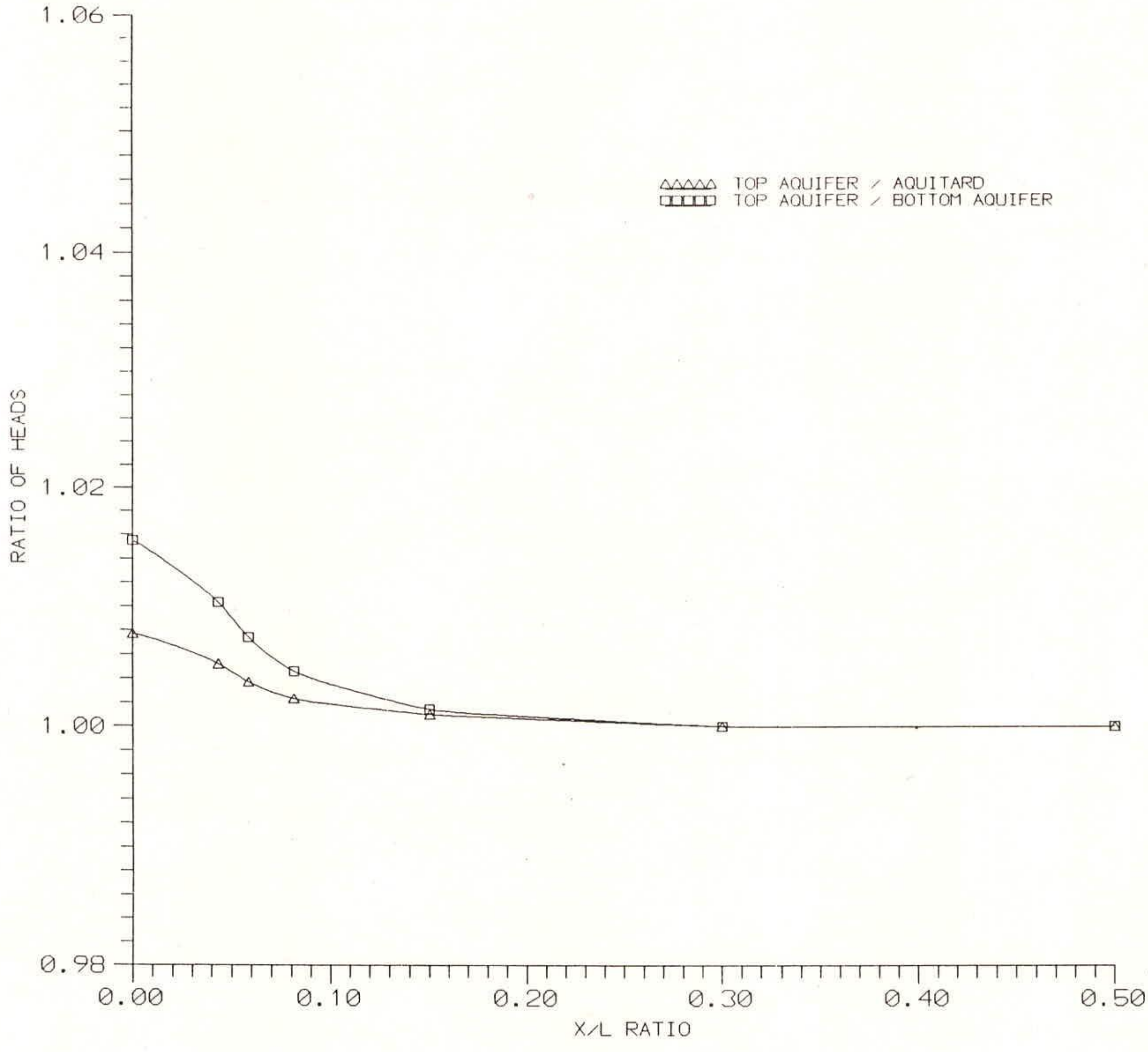

FIG.9(C) RATIO OF HEADS IN TOP AQUIFER TO BOTTOM AQUIFER AND TO AQUITARD FOR THICKNESS RATIO OF TOP AQUIFER TO BOTTOM AQUIFER = 1.10

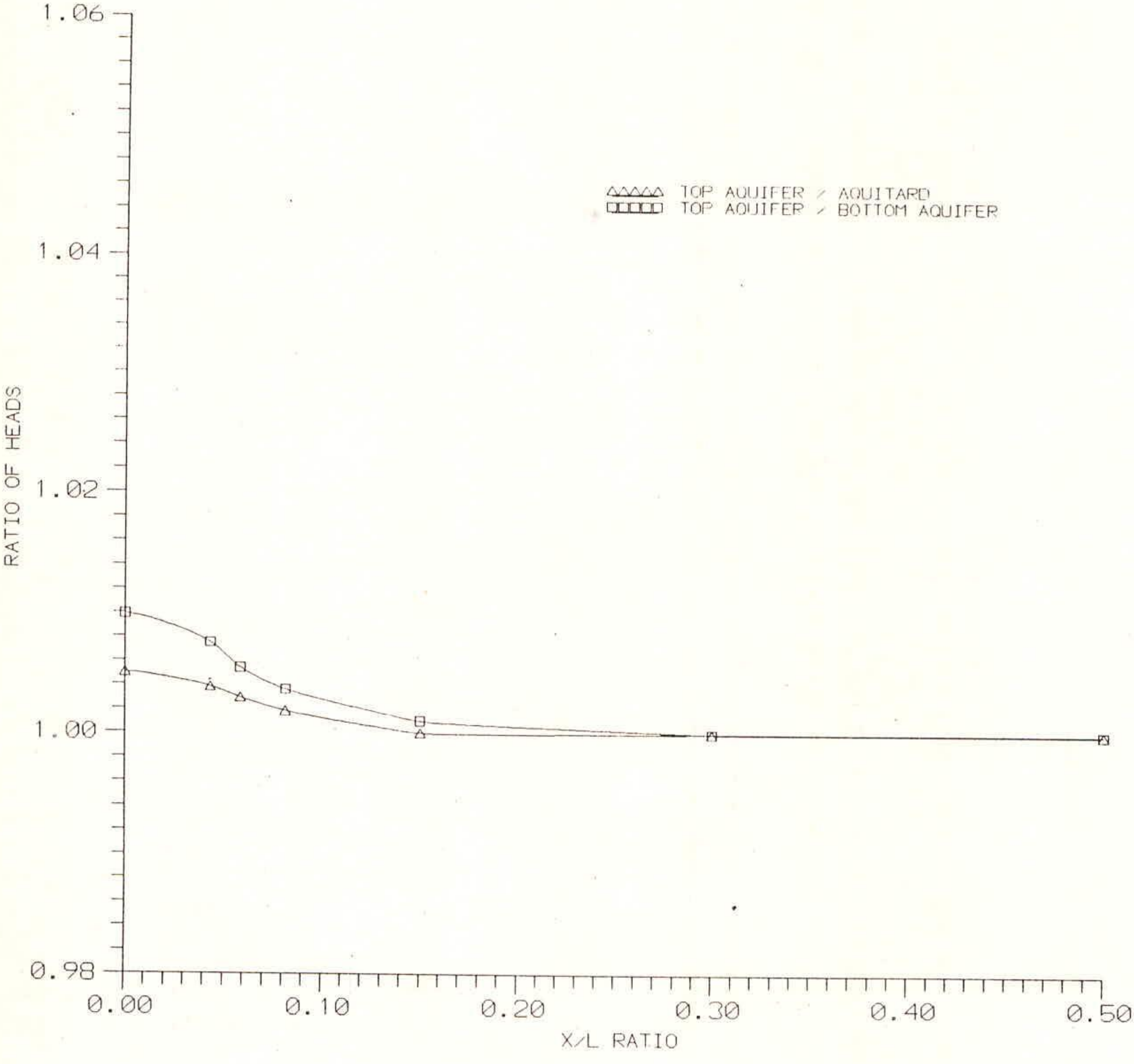

FIG.9(D) RATIO OF HEADS IN TOP AQUIFER TO BOTTOM AQUIFER AND TO AQUITARD FOR THICKNESS RATIO OF TOP AQUIFER TO BOTTOM AQUIFER = 1.80

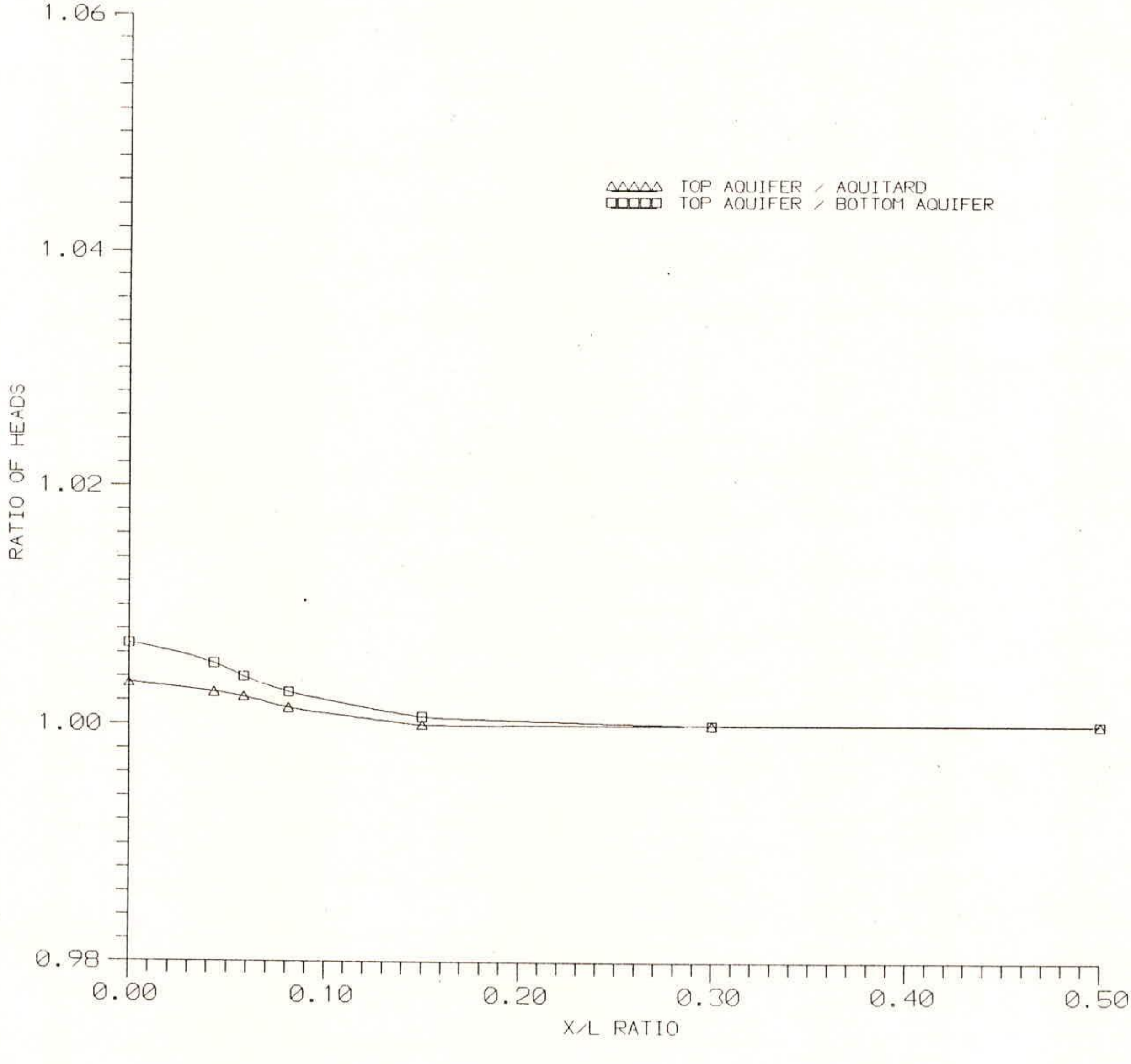

FIG.9(E) RATIO OF HEADS IN TOP AQUIFER TO BOTTOM AQUIFER AND TO AQUITARD FOR THICKNESS RATIO OF TOP AQUIFER TO BOTTOM AQUIFER = 3.00

aquifer to bottom aquifer and also for the top aquifer to aquitard are gradually decreasing when the ratio of thicknesses for the top aquifer to bottom aquifer increases. Also, obviously the difference between these head ratios is diminishing and approaching unity for higher aquifer thickness ratios (AFTR) marking uniform potentials everywhere in the system [Fig.9(E)].

Precisely, for a given thickness of the aquitard, if the top aquifer is thicker by more than three times that of the bottom aquifer, then the influence of the aquitard is not felt in the system for the given set up. Also, it is clear from previous discussion that the influence of the aquitard is vanishing in the system when it is placed below a depth greater than three times its thickness.

Table 3 Ratio of average discharge per unit width in the unconfined top aquifer and confined bottom aquifer for different aquifer thickness ratios (AFTR) while keeping aquitard depth ratio (ATDR) constant

Cases	Aquifer thickness ratio (AFTR)	Aquitard depth ratio (ATDR) while thickness of aquitard varies	Ratio of average discharge per unit width in top and bottom aquifer
a	0.40	2.15	0.98
b	0.58	2.15	0.97
c	0.79	2.15	0.98
d	0.95	2.15	0.98
e	1.08	2.15	0.97
f	1.51	2.15	0.97
g	2.22	2.15	0.98

In order to investigate the effect of aquitards of different thicknesses on the flow, several cases have been simulated by changing aquitard thickness. In all these cases the aquitard depth ratio (ATDR) has been kept constant while changing the thickness of the aquitards. For individual cases, the average discharges per unit width for the top and bottom aquifers as well as for the aquitard are computed.

The average discharges are plotted against the aquifer thickness ratios (AFTR) in Fig.10. The discharge from the aquitard is negligibly small for all the cases, as expected. Apparently,

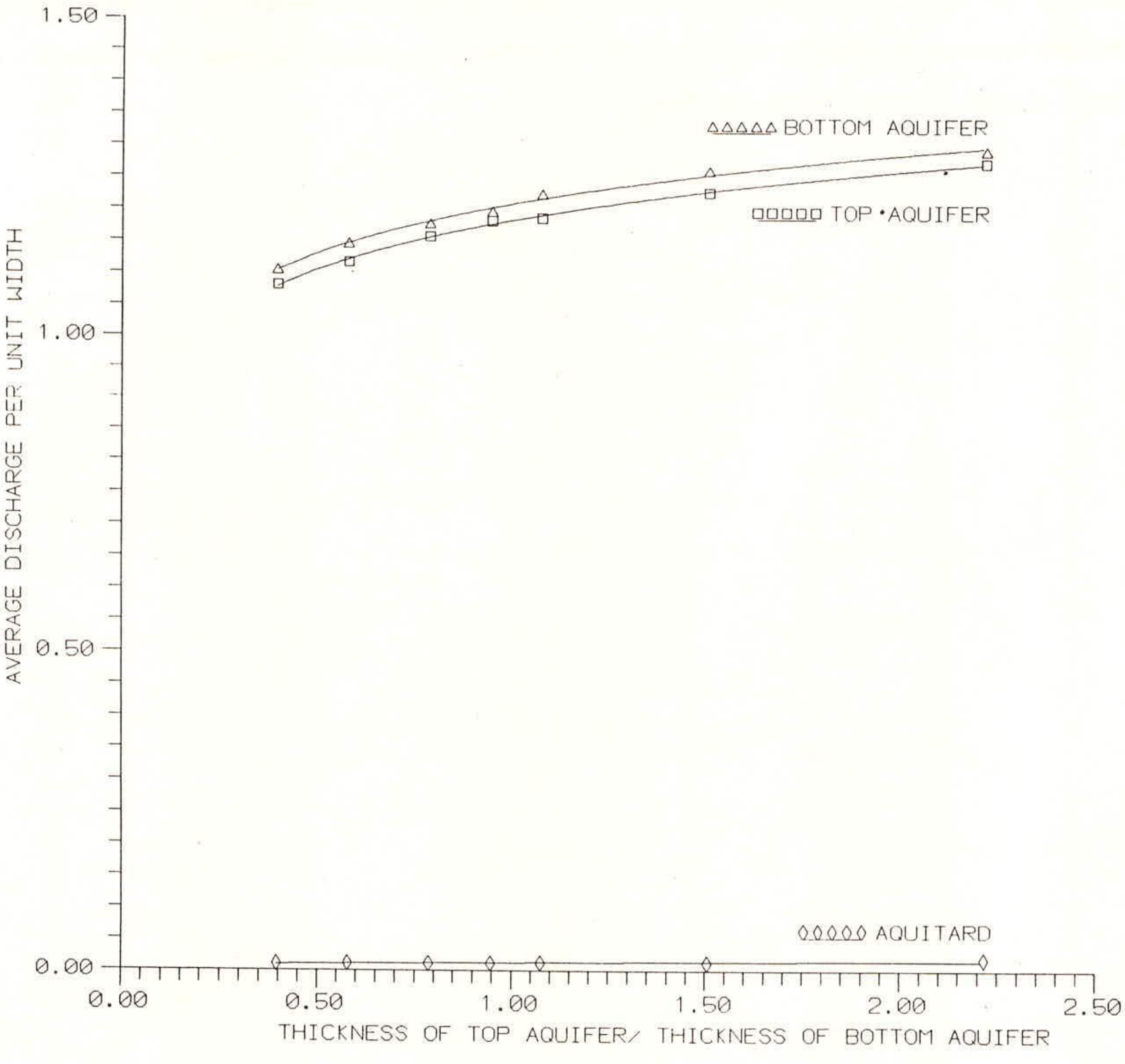

FIG.10 THICKNESS RATIO OF TOP AQUIFER TO BOTTOM AQUIFER Vs. AVERAGE DISCHARGE PER UNIT WIDTH FOR CONSTANT AQUITARD DEPTH RATIO

only vertical flow is occurring through the aquitards. Again, the average discharge of the bottom aquifer seemed to be a little higher than that of the top aquifer for all the cases. This may be attributed to the vertical flow taking place through the aquitards and discharging through the bottom aquifer to the constant head boundaries. However, the flow tends to become uniform in both the aquifers when the influence of aquitards gradually diminish at larger aquifer thickness ratios (AFTR).

6. CONCLUSION

A hypothetical aquifer-aquitard system with a static water body at its centre as a source of recharge with noflow boundaries and constant head river boundaries has been subjected to investigation. A simplified set up has been employed to examine the hydraulic potential distribution and flow pattern under steady state condition. The analysis brings forth the following aspects of the static waterbody-aquifer-aquitard system devised in the present study:

(a) For a given thickness of the aquitard, when the top aquifer is thicker by more than three times that of the bottom aquifer the influence of the aquitard is not felt significantly in the system.

(b) The influence of the aquitard is found vanishing in the system when the aquitard is placed below a depth greater than three times its thickness.

(c) The horizontal discharge from the aquitard is insignificant while vertical flow is predominant.

(d) The average discharge from the bottom aquifer is slightly more than that of the top aquifer for constant aquitard depth ratios (ATDR), which may be attributed to the vertical flow to the bottom aquifer through the aquitards.

(e) The flow tends to become uniform in both the top and bottom aquifers when the influence of aquitards starts diminishing for larger aquifer thicknesses ratios (AFTR) as well as aquitard depth ratios.

7. REMARKS

The study is expected to have evolved a methodology in the analysis of complex aquifer-aquitard systems with source water bodies. Scope for investigation of similar kind of problems is demonstrated as well. However, generalisation would be possible only after considering various scenarios with a range of hydraulic and flow parameters. Towards generalisation, further studies along similar lines can be formulated by introducing following aspects to cover wider scenarios:

(1) For a range of values of head causing flow (i.e. difference between the heads in water body and the river boundary)

(2) For different ranges of hydraulic conductivity as well as storage coefficient values of aquitards and aquifer.

(3) Introducing more number of aquitards/ leaky layers in the system at different depths

(4) Comparison of potential and flow characteristics for different scenarios in the vertical plane

(5) Making the flow three dimensional by removing noflow boundaries and introducing drains/ rivers.

(6) For different ratios of water body surface area to total area of the system.

(7) By incorporating influence of flow towards wells/ subsurface drains

(8) By considering variable recharge from top surface and evaporation losses

(9) For non-uniform recharge within the water body as well as transient recharge from the source

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