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EFFECT OF DISCONTINUOUS AQUITARD ON THE SEEPAGE FROM A STATIC WATER BODY

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ABSTRACT

In semi-arid areas of India percolation tanks are in use for artificial recharge of the aquifer. However, the efficacy of the percolation process has not yet been studied in terms of the parameters which influence the recharge. The seepage from a surface water body is dependent on the hydrogeological setup of the region and aquifer characteristics. Present study investigates the seepage pattern beneath a recharging source. For the purpose of investigation, a case study with recharge/discharge sources in a two layer aquifer system separated by a barrier with possible discontinuities is considered. A three-dimensional groundwater flow model is employed for simulating flow in the system. The recharging source, a pond/lake, is positioned at the centre of the aquifer system in plan. A number of cases have been studied by making openings of varying widths in the aquitard, symmetrically located below the recharge-source to analyse the impact of a discontinuity on seepage distribution. This report deals with the influence of the dimensions of the opening in the aquitard and the aquifer characteristics on the discharge as well as on the hydraulic potentials. Distribution of hydraulic potentials in the entire system for different diffusivity values and for various aquitard openings are analysed. A number of cases were studied and results are presented graphically.

The analyses revealed the following: (i) So long as the hydraulic diffusivity (S/T) is kept constant the fractional seepage, F_{sb} to the aquifer system is invariant. (ii) The zone of influence of the recharge source decreases as the hydraulic diffusivity increases. (iii) Even for a very minor discontinuity the contribution of seepage to the second aquifer is significantly high. (iv) Further, the seepage is predominantly to the bottom aquifer irrespective of the dimension of discontinuity in the aquitard for large ratios of hydraulic diffusivity. The study revealed that diffusivity has significant effect on the efficiency of a recharge pond rather than the individual aquifer parameters. Also, it is observed that even minor discontinuity in the barrier causes significant change in the seepage pattern.

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Fig. 26 Percentage Opening versus Seepage to the top as well as bottom aquifer respectively for different values of Diffusivity

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1.0 INTRODUCTION

Designing and managing artificial recharge methods offer wider scope for optimal use of aquifers. In arid and semi-arid regions artificial/ managed recharge is achieved by means of percolation tanks and small lakes. However, geohydrological aspects often elude attention while locating such storage-recharge tanks. Any inefficiency of such projects, detected later on, in improving the aquifer conditions could have possibly sprang up from inadequate knowledge of the seepage characteristics within the aquifer system. For effective utilisation of the potential of storage in the aquifer system, it is desirable to understand the seepage characteristics of the system under various geological set-up as well as stress conditions.

1.1 Earlier Studies

Existence of low permeable clay layers (continuous/ discontinuous) within an aquifer system can influence seepage from the source as they can act as continuous/ discontinuous barriers to flow. It is desirable to understand in advance what kind of influence such barriers may cause and to what extent. Studies on flow patterns surrounding lakes/ surface water bodies with reference to various contexts have been reported (*Mc Bride and Pfannkuch,1975; Winter 1976, 1983, 1986; Munter 1981*). Studies regarding the effect of anisotropy and system geometry on seepage and the distribution of seepage through lake beds are available (*McBride and Pfannkuch, 1975; Pfannkuch and Winter, 1984; Winter and Pfannkuch, 1984*). Numerical simulation techniques have been in use to lake-groundwater interaction studies (*Winter, 1976; Munter, 1981; Nield et al. 1994*). Townley and Davidson (*1988*) investigated lake-aquifer interaction to develop relationships between measurable geometrical and aquifer parameters and the bulk behaviour of the flow system using two dimensional geometries. Type curves for the assessment of seepage from a lake in a homogeneous aquifer medium have been developed by Singh and Seethapathi (*1990*). The influence of a continuous aquitard on the flow distribution in a multilayer aquifer system has also been examined (*Jose and Seethapathi, 1996*).

1.2 Objectives

Most of the studies conducted are more or less unique in their approaches and pertain to specific regions of interest. As such, generalisation of results may not be appropriate and their usefulness lies solely in the methodologies. Studies pertaining to multi-layer aquifer systems are meagre, too (*Marsily et al.,1978; Lafe et al., 1981; Jose and Seethapathi, 1996)*. As such, investigations regarding the influence of discontinuous aquitards on seepage are not immediately available. Though the effect of specific aquifer parameters viz., storage coefficient (S) and transmissivity (T) on the system behaviour is studied to some extent, the combined effect of S and T on the potential distribution and on the seepage from a recharge source is yet to be analysed in detail. Existence of low permeable layers (continuous/ discontinuous) within an aquifer system can influence seepage from the source as they can act as barriers to flow. The present study, therefore, aims at evaluating the influence of a discontinuous barrier on the seepage from a static recharge-source.

2.0 CONCEPTUALISATION

Particular geohydrological set up may influence seepage from a surface water body to an aquifer system. The seepage characteristics from a recharge source in a multi-layered aquifer system, containing a discontinuous flow-barrier (an aquitard), are investigated. The scheme of the layered aquifer system under investigation is given in figure-1. A square-shaped lake (*the source*) of size *2w x 2w* is located at the centre of the plan area of an isotropic aquifer system having dimensions *2L x 2L*. The bottom of the aquifer system conforms to an impermeable bed at depth *D*.

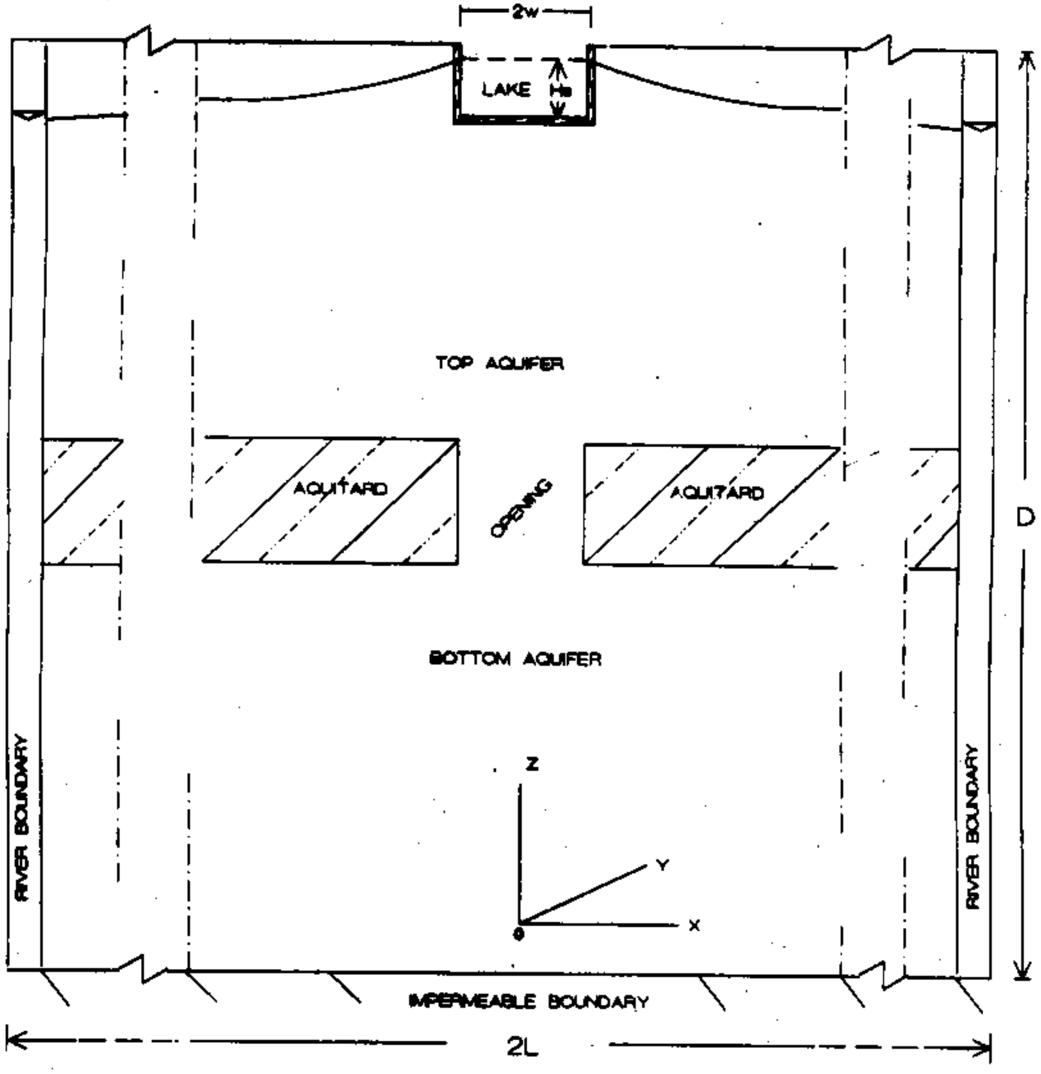


Fig. 1 Vertical section of the aquifer system with a discontinuous barrier placed in the middle

An aquitard of very low permeability is positioned in the middle of the aquifer system. This partitions the system into an unconfined top aquifer and a confined/ semi-confined bottom aquifer. The lateral boundary of the aquifer system is a fully penetrating constant head river (*the sink*) on two sides while the other two sides are no-flow boundaries. These boundaries have been located at sufficiently large distance (*L*) from the source. The sides and bottom of the lake are assumed to have a layer of sediments of low permeability. Difference between the head in the source and that in the sink (*Hb*), the head causing- flow (*dH*) is adequate to induce flow through the aquifer system. Appropriate parameter values have been assigned for the aquitard so as it to act like a flow barrier between the top and bottom aquifers.

2.1 Dicretisation

The total depth of the aquifer system to an impermeable bed is 100m. The difference of heads in the water body and the constant head boundary (the head-causing-flow) is 9m. The total surface area in plan is about 700 times that of the waterbody. The ratio of any lateral side of the plan area to that of the water body is approximately 25. The choice of hydraulic conductivity as well as storage coefficient values is well in conformity within the acceptable ranges. Hydraulic conductivity of the aquitard is kept lesser by six orders of magnitude than that of the aquifer medium.

To facilitate the finite difference application of the flow equations, the aquifer system is discretised into a number of rectangular grids (51x51) and ten layers. Variable grid spacing is used to get detailed information from finer grids beneath and around the source. In order to study the effect of discontinuity in the lateral extent of the aquitard, provision is made in the discretisation. Uniform hydraulic conductivities are assumed for both the horizontal and vertical directions in a layer. Aquifer parameters, however, may vary from one layer to another. Parameter values for the aquifer and the aquitard portions have been assigned suitably. The sides and bottom of the lake are assumed to have a layer of sediments with smaller permeability compared to aquifer medium. Transient simulation of flow is carried out. The stress period, consisting of several time steps, of the simulation being kept sufficiently long so as to attain steady state situation. The water level in the water body (source) being maintained constant throughout the simulation. The distribution of hydraulic potentials in the medium and volumetric details have been obtained, at the end of selected time steps during the stress period and also at the end of the simulation period, for further analysis.

3.0 METHODOLOGY

In the present study, the finite difference groundwater flow model, MODFLOW is used for simulating flow in the aquifer system. Development of the finite difference model of the flow equation with boundary conditions and solution procedures can be found elsewhere (*Mc Donald and Harbaugh, 1984*).

3.1 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

In general, S_s, K_{xx}, K_{yy} and K_{zz} are functions of space whereas h and W are functions of space and time. The above equation describes groundwater flow under non-equilibrium conditions in a heterogenous and anisotropic medium. Thus, 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. Since analytical solutions of the flow equation referred above are rarely possible, numerical methods may be used to arrive at approximate solutions.

4.0 ANALYSIS AND DISCUSSION

Simulation of flow in the aquifer system is carried out for varying set of parameter values and different dimensions of discontinuities in the aquitard. The general assumptions involved in the formulation of the study are enumerated below:

(a) the layers are continuous and parallel to the ground surface;
(b) the hydraulic parameters vary from layer to layer;
(c) uniform horizontal and vertical hydraulic conductivities for individual layers;
(d) impermeable lower boundary at finite depth;
(e) flow being guided by Darcy's principle;
(f) transient simulation of the flow;
(g) flow is predominantly toward the fully penetrating constant-head river boundaries;
(h) head (causing flow) in the static water body remains constant throughout the simulation;
(i) uniformly distributed seepage from the water body; and
(j) no change in the properties of water during the stress period.

In the present study, the effect of discontinuity in the aquitard placed half-way within the aquifer system on the seepage from a small lake is analysed. For the purpose of analysis following quantities/ ratio have been defined and used.

(a) *Distance ratio, X/L*: Ratio of distance from the centre of the source to any arbitrary point in the direction of the X-axis to the distance between the source and the sink.

(b) *Head Causing Flow, dH*: The difference between hydraulic head in the source and that in the sink which induces the seepage.

(c) *Aquifer potential , h:* The arbitrary variable representing hydraulic head/ potential in the aquifer.

(d) *Head in the Boundary,* H_b: Hydraulic head in the constant head river boundary.

(e) *Percentage Opening, Op*: Discontinuity in the aquitard expressed as a percentage with respect to the dimension of the source water body.

(f) *Fractional Seepage,* F_{sb} : The seepage from the source to the bottom aquifer expressed as a fraction of the total seepage to the system.

(g) *Normalised Hydraulic Potential,* $(h - H_b)/dH$: The ratio of difference between hydraulic potential at any point in the aquifer and that in the boundary to the head causing flow.

(h) *Hydraulic Diffusivity, S/T*: Ratio of storage coefficient to transmissivity value.

(i) *Reversal Point,* X_R: A point on the X axis between the source and the sink at which the potentials are the same for both the top and the bottom aquifers.

An aquitard of very low permeability is assumed and is positioned in the middle of the aquifer system. When the aquitard is full without any discontinuities, essentially no flow takes place to the bottom aquifer. Discontinuity (opening) of varying dimensions, symmetrical with respect to the water body, has been provided in the aquitard through which seepage enters the bottom aquifer. The resulting detached space with which the discontinuity has been introduced is assumed to be filled with same material as that of the aquifer above. The discontinuities have been quantified as percentage openings (O_p) of the width of the source body.

Simulation of flow has been carried out for a number of percentage openings and combination of aquifer parameters while maintaining the physical aspects of the system unaltered. The distribution of hydraulic heads/ potentials (h) in the aquifer and volumetric details have been obtained at the end of the simulation period. Hydraulic heads/ potentials normalised with respect to the head causing flow, $(h - Hb)/dH$, is used for the analysis. The seepage from the source to the top and the bottom aquifers and the discharge to the river boundaries have been computed subsequently.

The effect of opening in the aquitard for different aquifer parameters both on the potential distribution and seepage have been studied. Various cases of study conducted for analysis are presented in figure-2 in the form of a matrix table.

S/T	% opening (O_p)												
	0	.003	.01	.02	.03	.04	.2	.5	1	4	7	30	100
.0540	x	x	x	x	x	x	x	x	x	x	x	x	x
.1081	x	x	x	x	x	x	x	x	x	x	x	x	x
.1500	x	x	x	x	x	x	x	x	x	x	x	x	x
.2162	x	x	x	x	x	x	x	x	x	x	x	x	x
.3027	x	x	x	x	x	x	x	x	x	x	x	x	x
.4000	x	x	x	x	x	x	x	x	x	x	x	x	x
.5045	x	x	x	x	x	x	x	x	x	x	x	x	x
.6000	x	x	x	x	x	x	x	x	x	x	x	x	x

Fig. 2 Matrix table of parameter combinations used in the study

The seepage from the source is computed both to the top aquifer and to the bottom

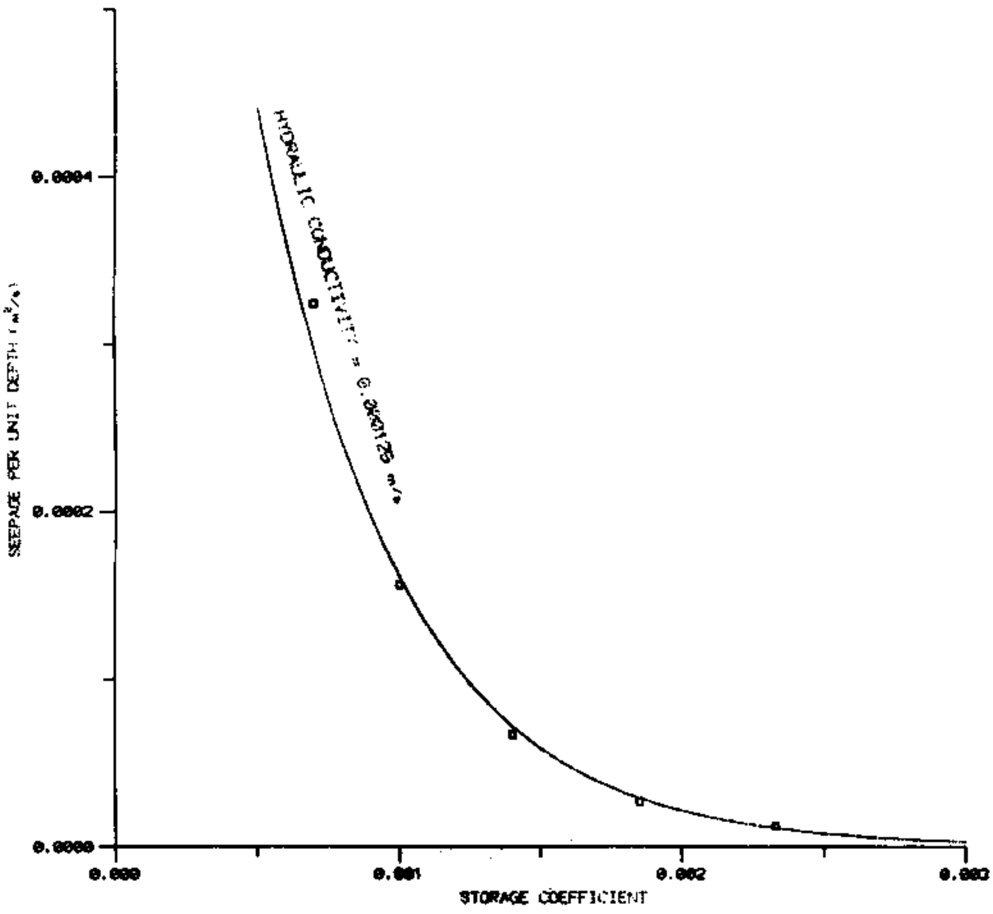


Fig. 3 Storage Coefficient versus Seepage per unit depth in the aquifer system for a given value of Hydraulic Conductivity

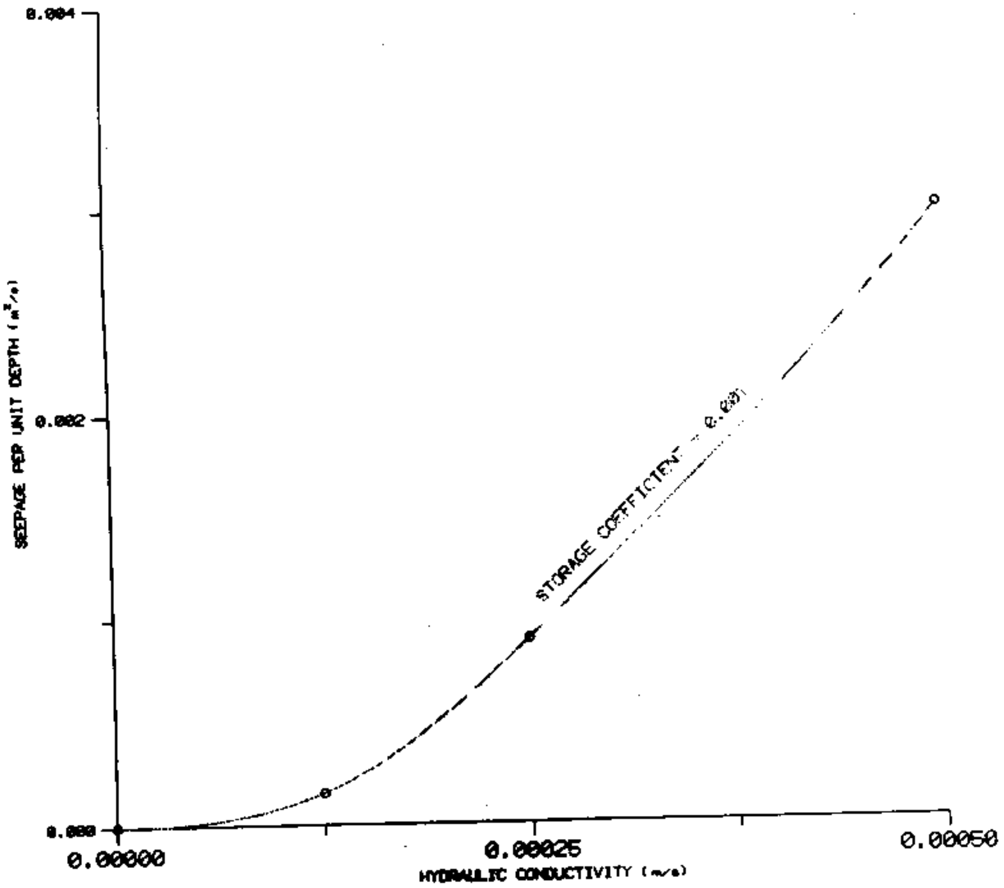


Fig. 4 Hydraulic Conductivity versus Seepage per unit depth in the aquifer system for a given value of Storage Coefficient

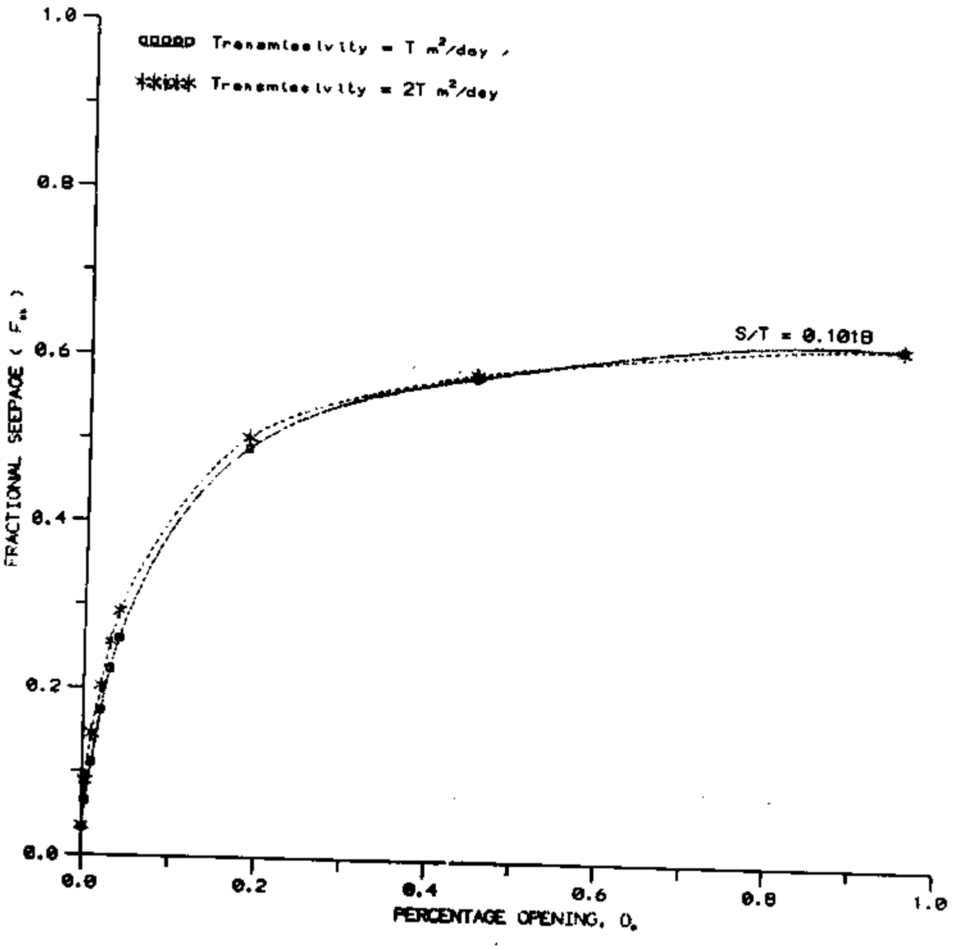


Fig. 5 Percentage Openings, O_p versus Fractional Seepage, F_{sb} for two different Transmissivity values while Diffusivity, S/T being kept constant

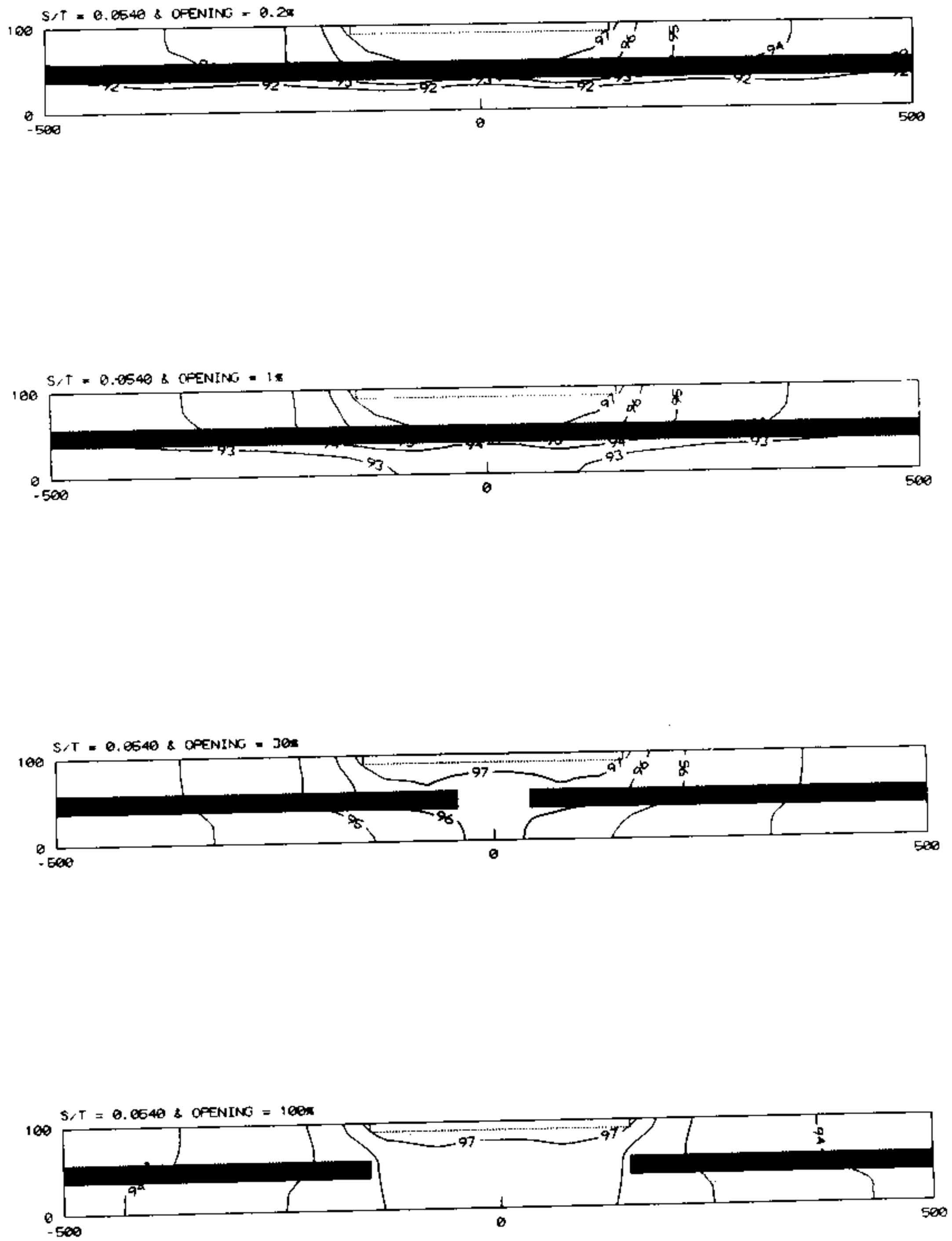


Fig. 6 Distribution of Hydraulic Potential in the aquifer system for a Diffusivity value, S/T = 0.0540 for Percentage Openings, O_P = 0.2%, 1%, 30% & 100%

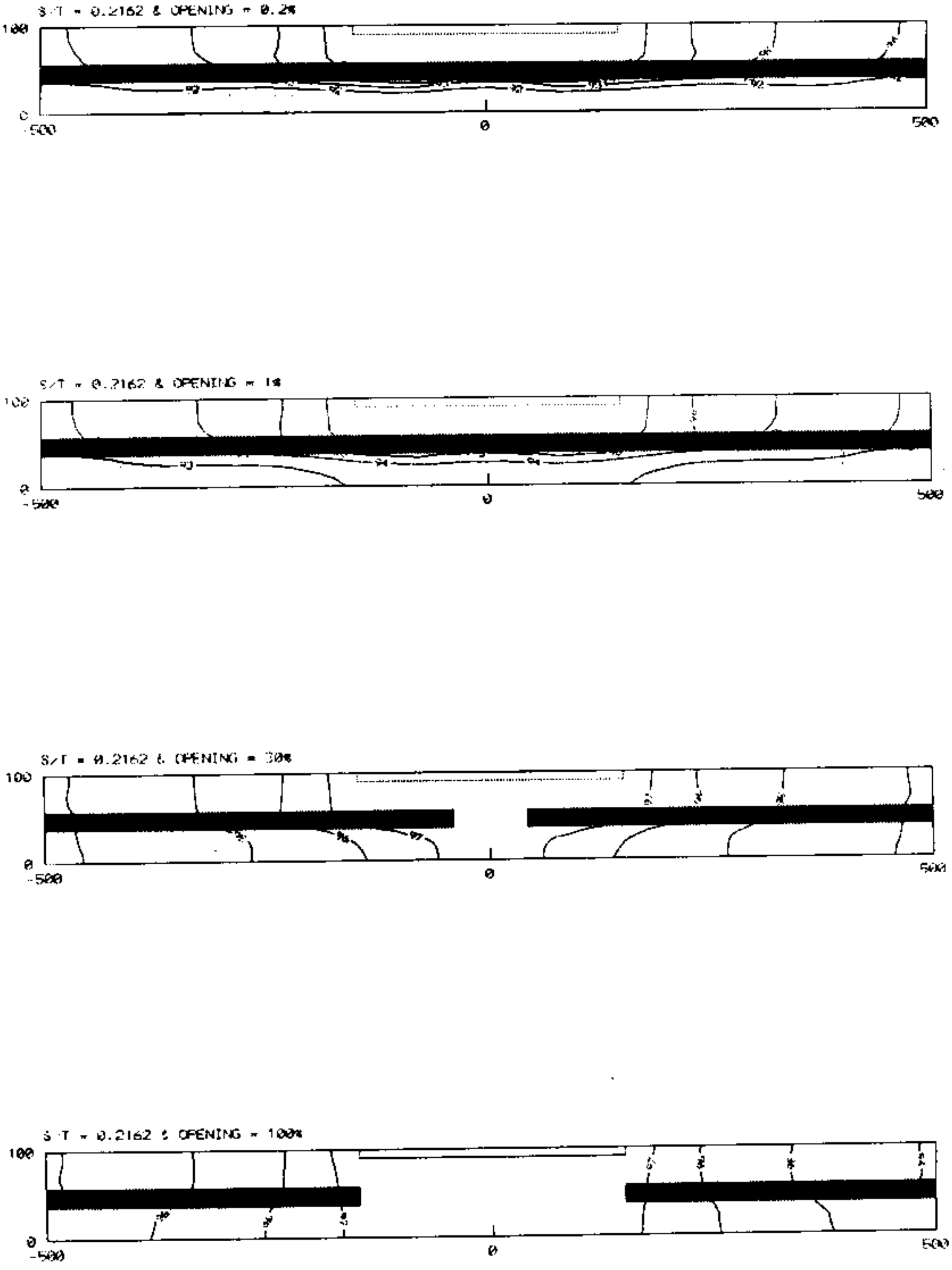


Fig. 7 Distribution of Hydraulic Potential in the aquifer system for a Diffusivity value, S/T = 0.2162 for Percentage Openings, O_P = 0.2%, 1% 30% & 100%

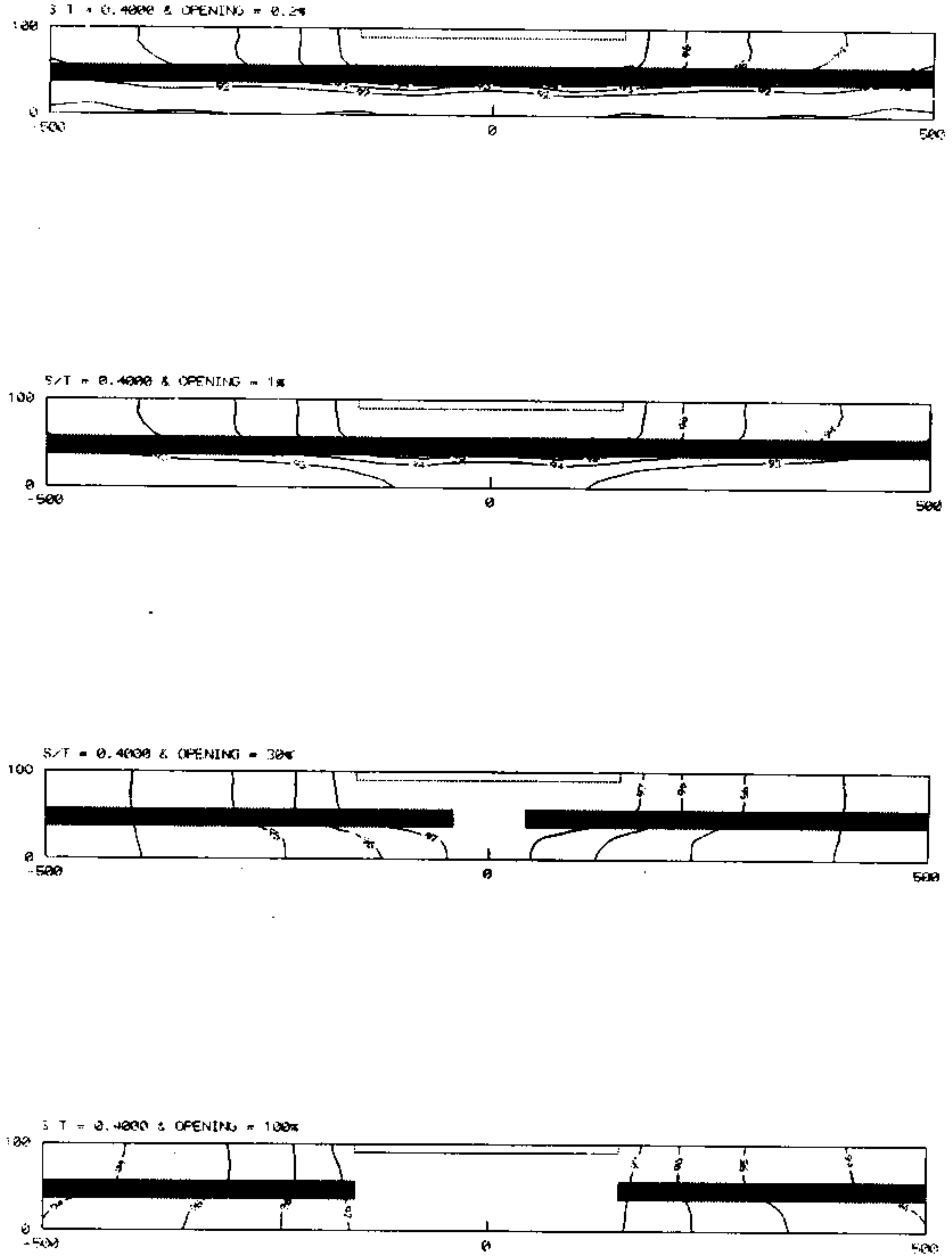


Fig. 8 Distribution of Hydraulic Potential in the aquifer system for a Diffusivity value, S/T = 0.4000 for Percentage Openings, O_P = 0.2%, 1%, 30% & 100%

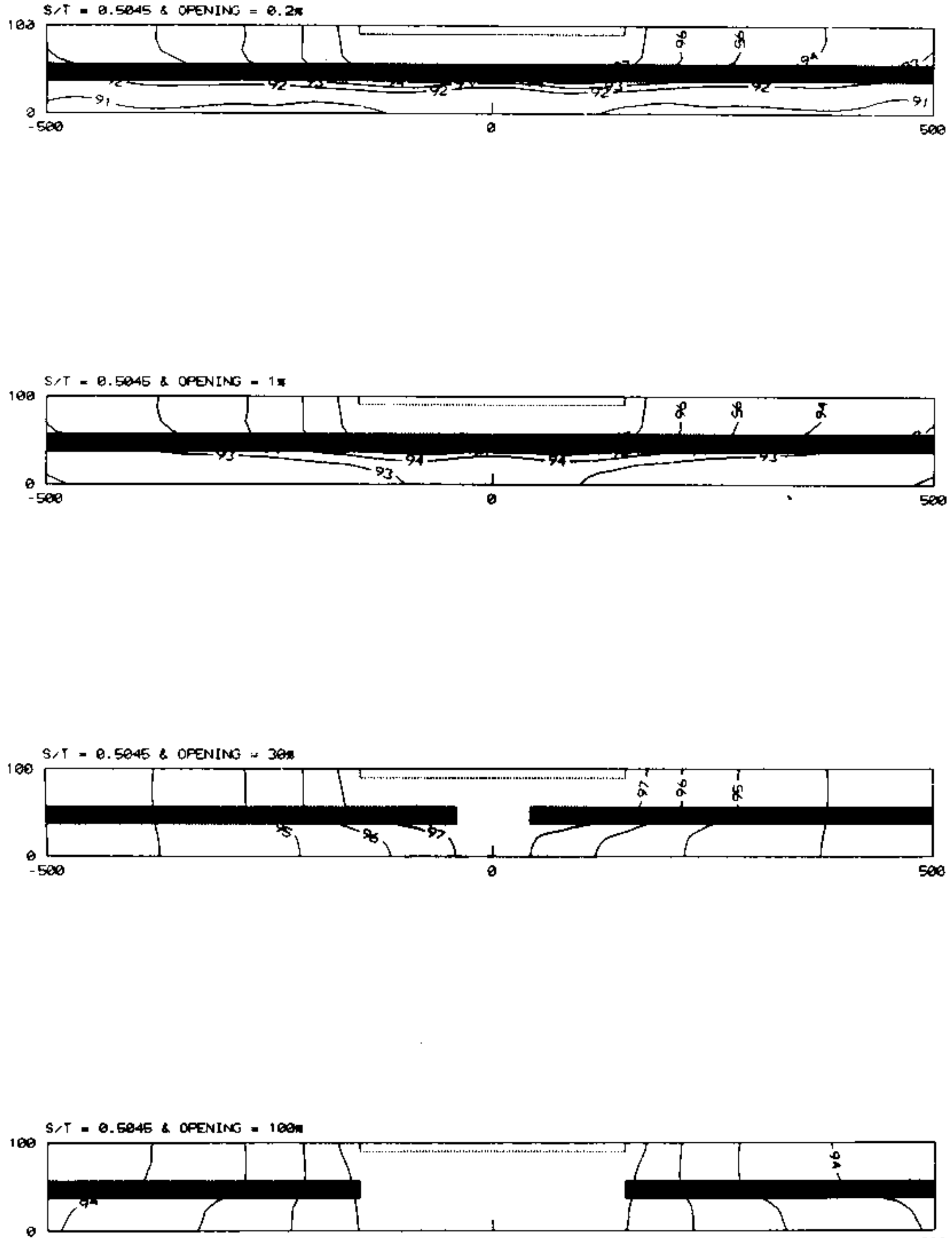


Fig. 9 Distribution of Hydraulic Potential in the aquifer system for a Diffusivity value, S/T = 0.5045 for Percentage Openings, O_P = 0.2%, 1%, 30% & 100%

aquifer. It is observed that the seepage bears a direct proportionality with respect to hydraulic conductivity for a given storage coefficient value. However, the relationship between seepage and the storage coefficient (S) is of inverse nature for a given value of hydraulic conductivity. It is evident that the seepage per unit depth being steadily increased with increasing values of hydraulic conductivities for a constant storage coefficient (Fig-3) while the seepage per unit depth is fast receding with increasing storage coefficient keeping the hydraulic conductivity constant (Fig-4). Thus, the seepage in the aquifer system is influenced by hydraulic conductivity (expressed as transmissivity, T) and storage coefficient, S in quite different manner. To facilitate analysis, seepage per unit depth occurring in the top as well as bottom aquifers have been normalised as a fraction of the total. This fraction, termed as the fractional seepage F_{sb}, bears certain relationship with the ratio of storage coefficient to transmissivity (hydraulic diffusivity, S/T). Precisely, the fractional seepage, F_{sb} is found to be invariant with respect to the hydraulic diffusivity (S/T) even while individual values of hydraulic conductivity and/or storage coefficient vary (Fig-5). It may be due to the nature of influence of storage coefficient and transmissivity on the seepage from the system. It is observed that the actual discharge from the system is sensitive to S/T even while the fractional seepage is invariant. Thus, all physical parameters being the same and with a constant diffusivity value, the seepage from the source to the bottom aquifer expressed as a fraction of the total seepage to the system (F_{sb}) remained unaltered even when individual values of S and T are varied. Therefore, fractional seepage, being a conserved quantity, has been used in the analysis in addition to other parameters such as seepage per unit depth to the top aquifer, seepage per unit depth to the bottom aquifer and distribution of hydraulic head/ potential in the aquifer system.

The equipotentials are drawn for various percentage openings and for different values of S/T. Figures-6, 7, 8 & 9 depict the potential distribution in the central section for percentage openings 0.2%, 1%, 30% & 100% for S/T=0.0540, 0.2162, 0.4 and

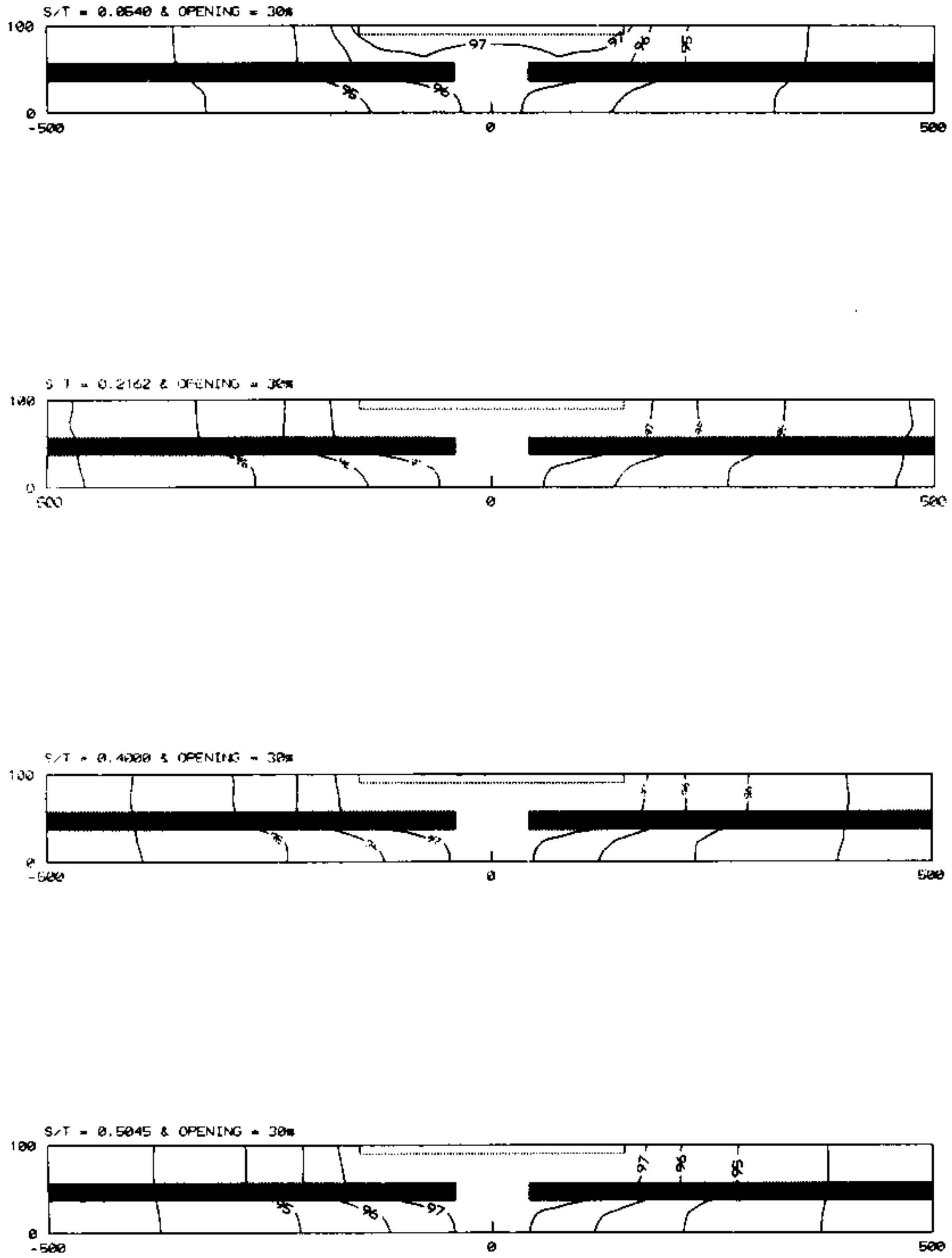


Fig. 10 Distribution of Hydraulic Potential in the aquifer system for a Percentage Opening, O_P = 30% for Diffusivity values, S/T = 0.0540, 0.2162, 0.4000 & 0.5045

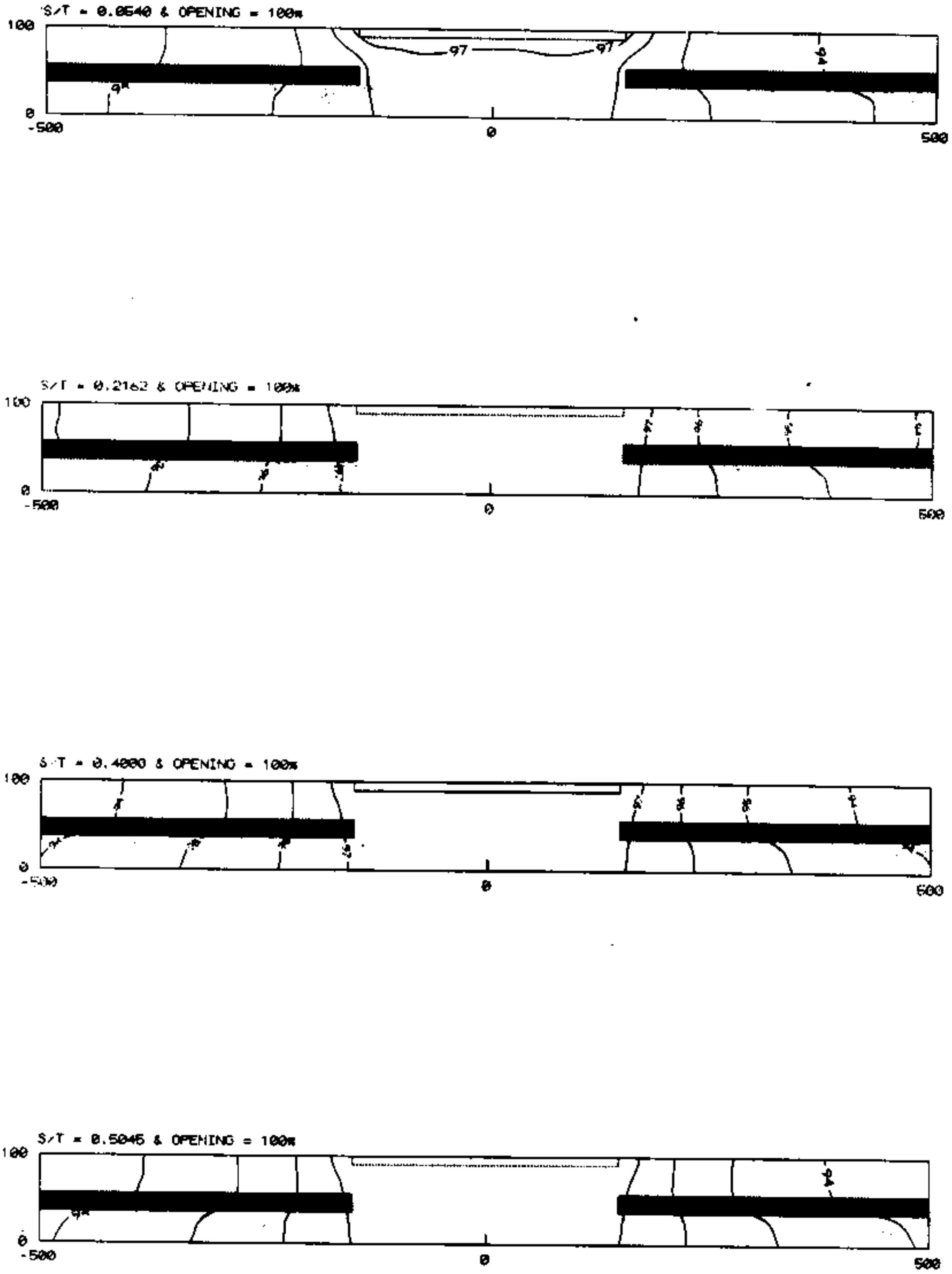


Fig. 11 Distribution of Hydraulic Potential in the aquifer system for a Percentage Opening, O_p = 100% for Diffusivity values, S/T = 0.0540, 0.2162, 0.4000 & 0.5045

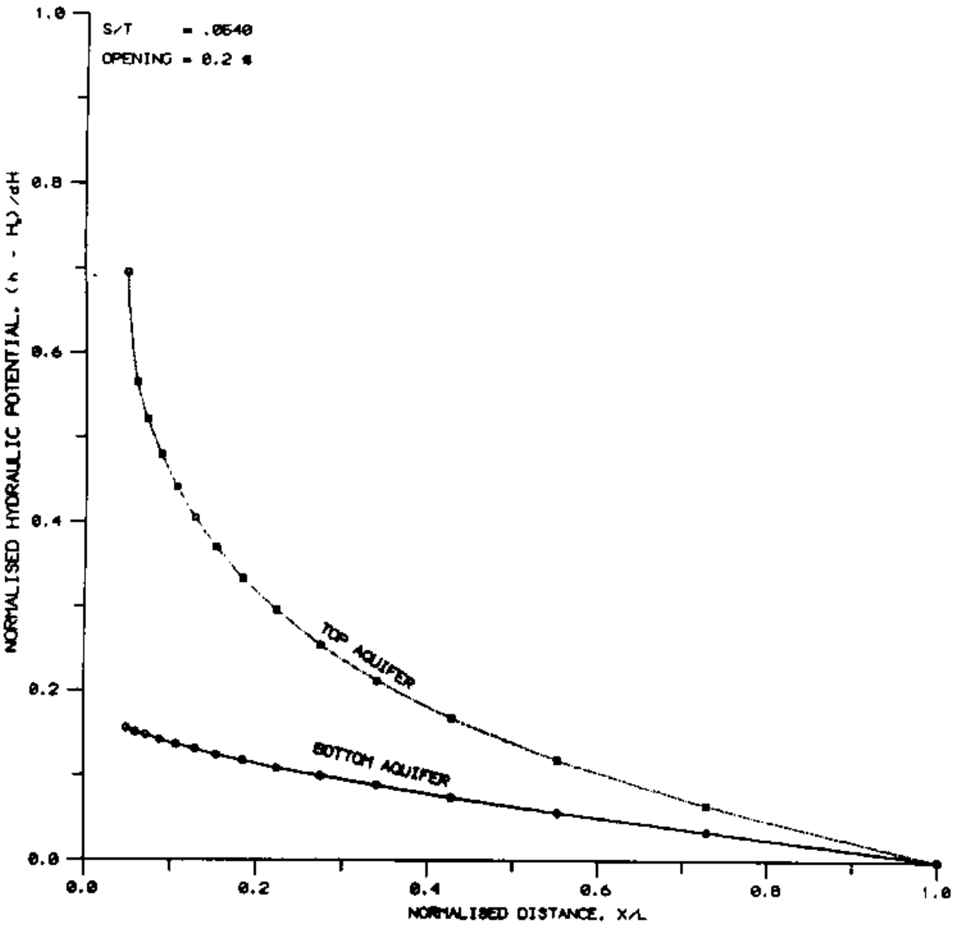


Fig. 12 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_p = 0.2% and Diffusivity, S/T = 0.0540

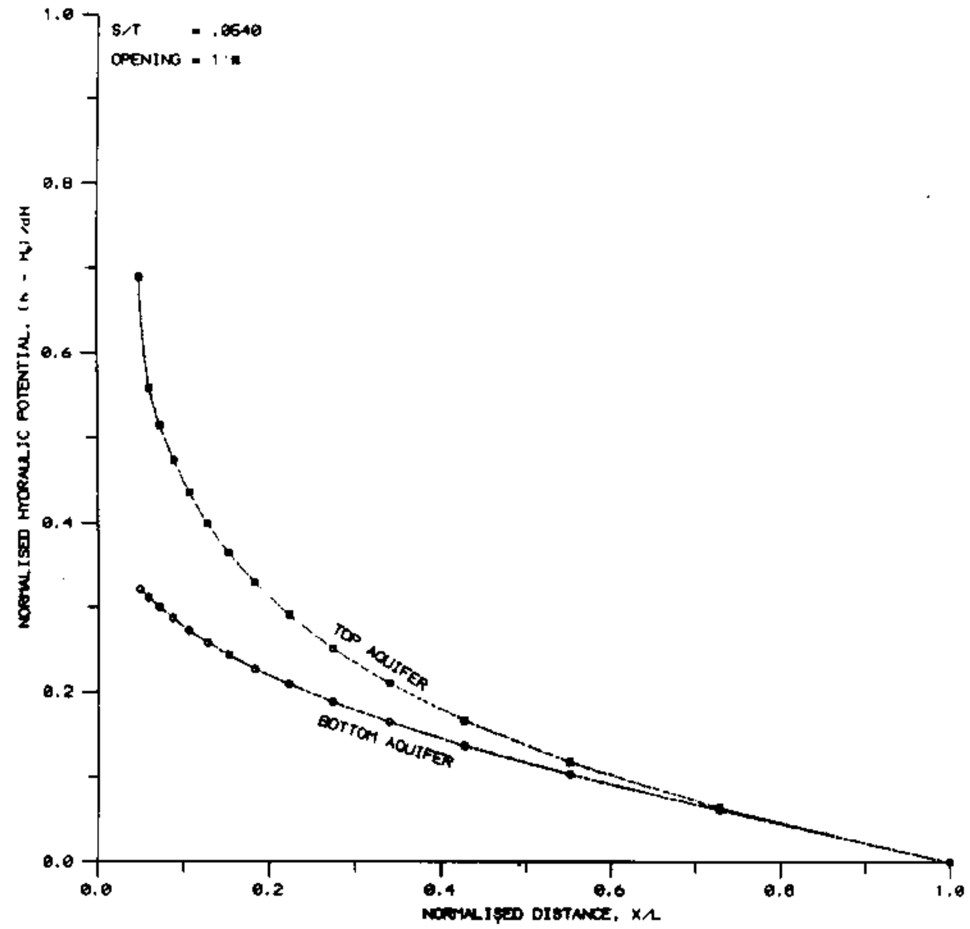


Fig. 13 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_p = 1% and Diffusivity, S/T = 0.0540

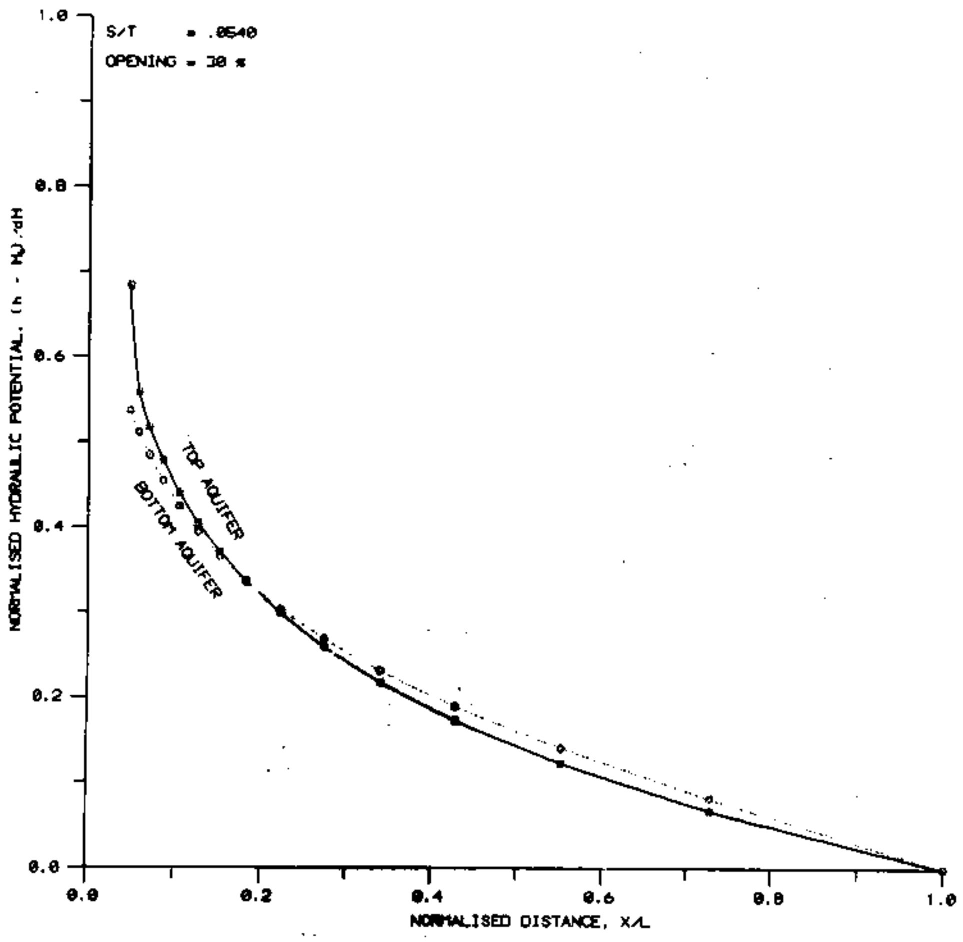


Fig. 14 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_p = 30% and Diffusivity, S/T = 0.0540

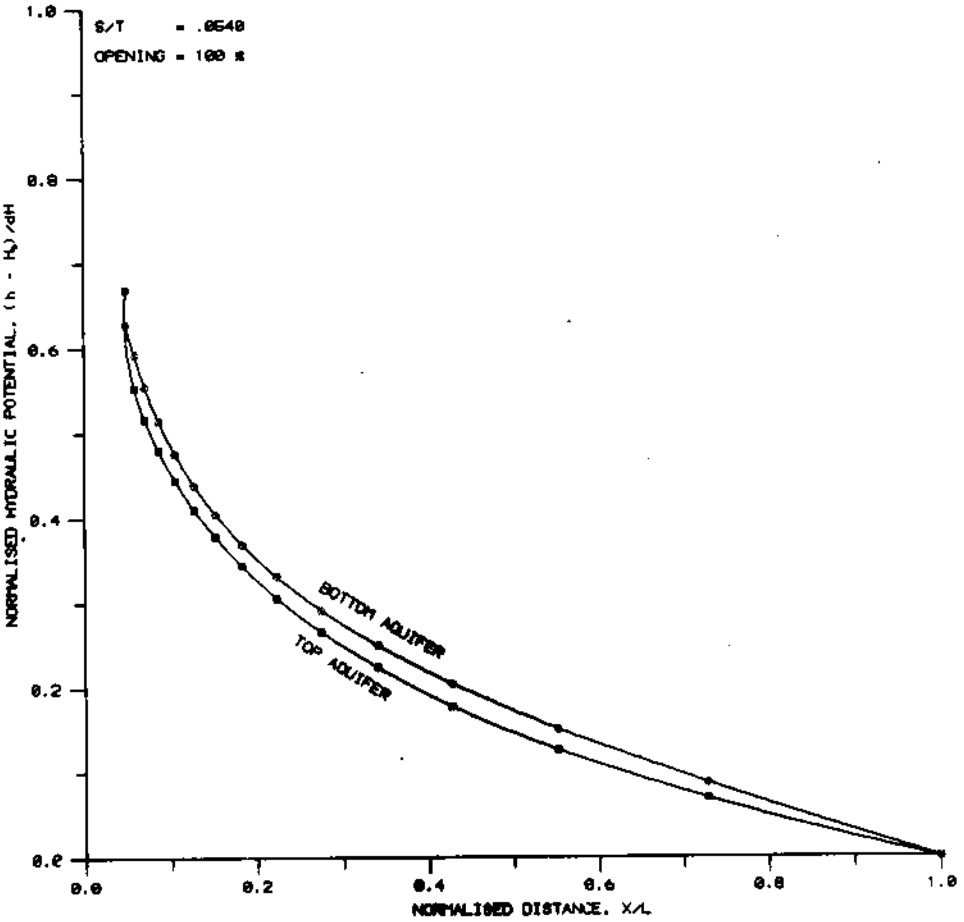


Fig. 15 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_P = 100% and Diffusivity, S/T = 0.0540

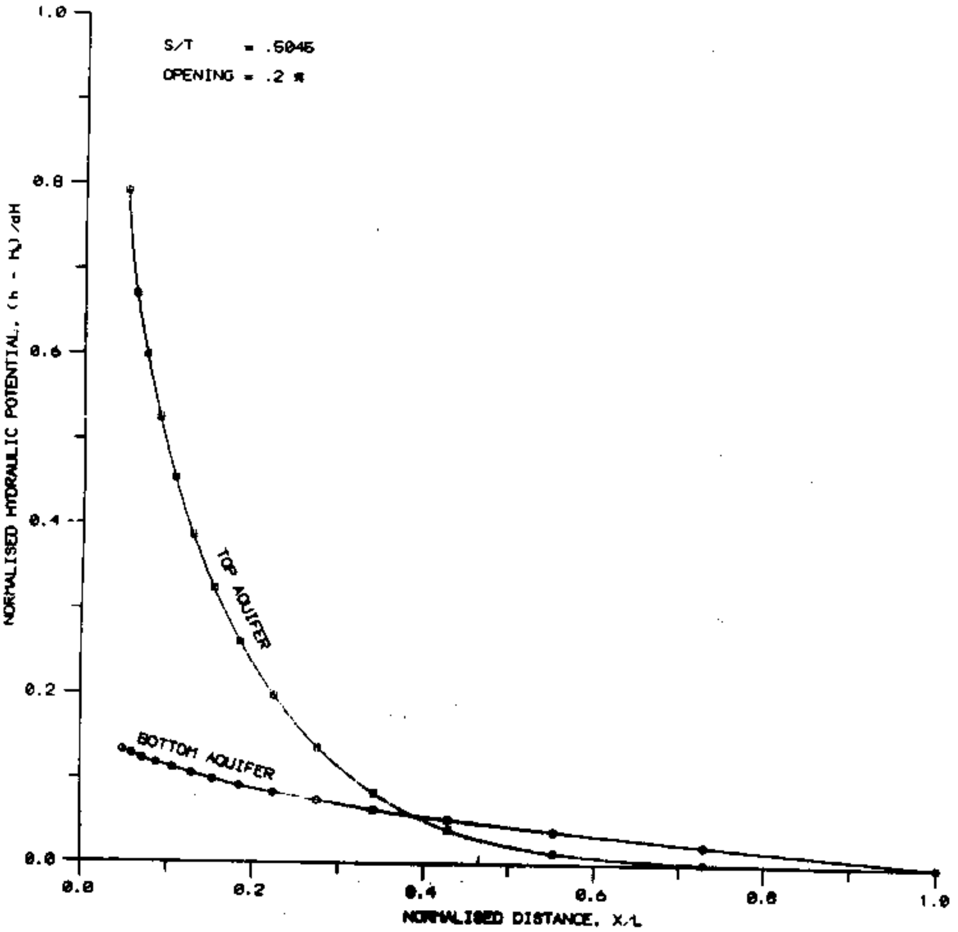


Fig. 16 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_P = 0.2% and Diffusivity, S/T = 0.5045

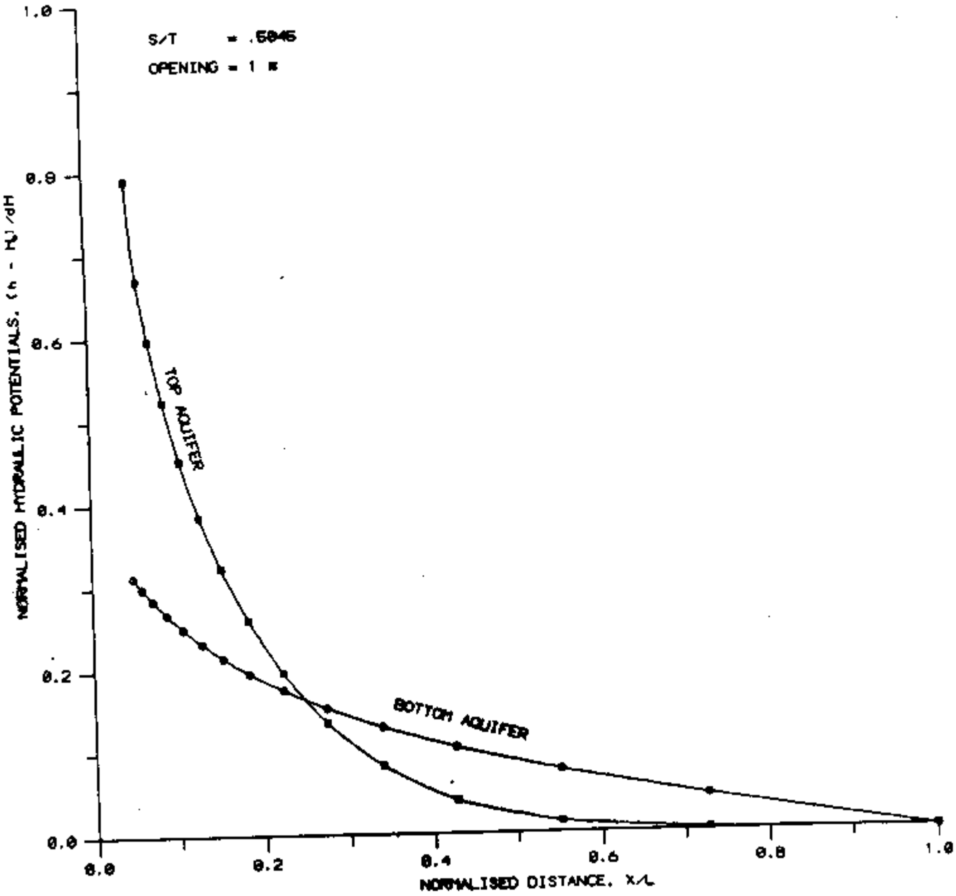


Fig. 17 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_P = 1 % and Diffusivity, S/T = 0.5045

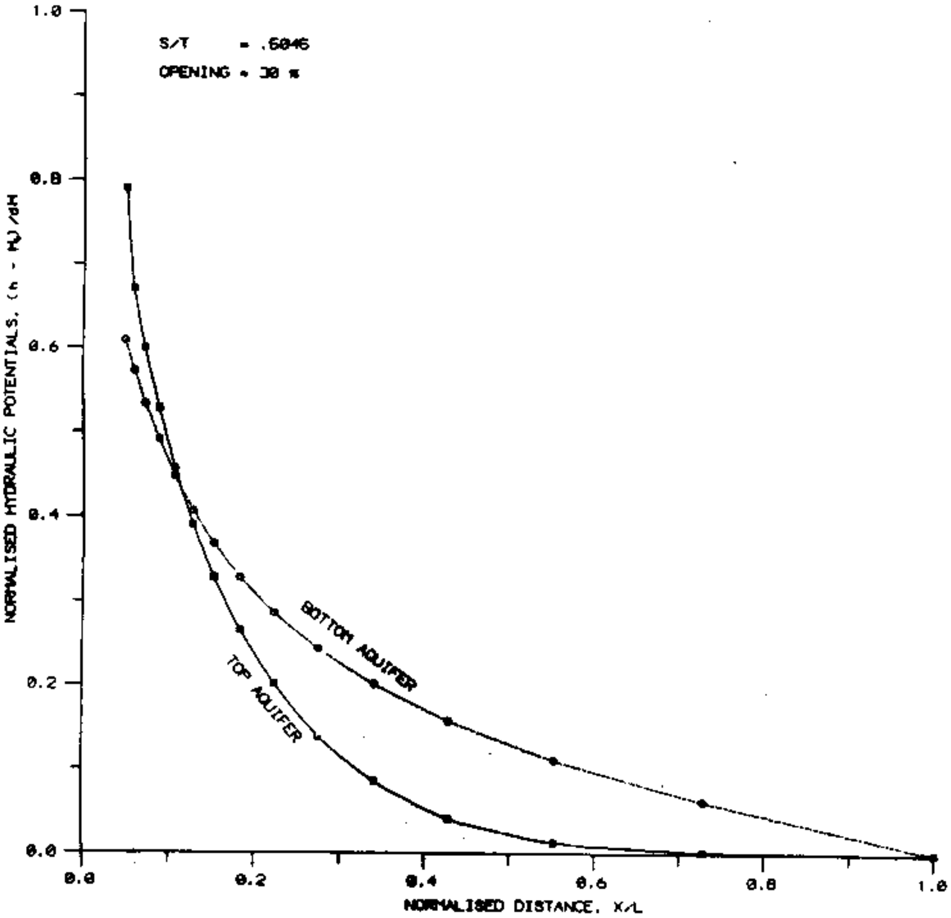


Fig. 18 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, $O_p = 30\%$ and Diffusivity, $S/T = 0.5045$

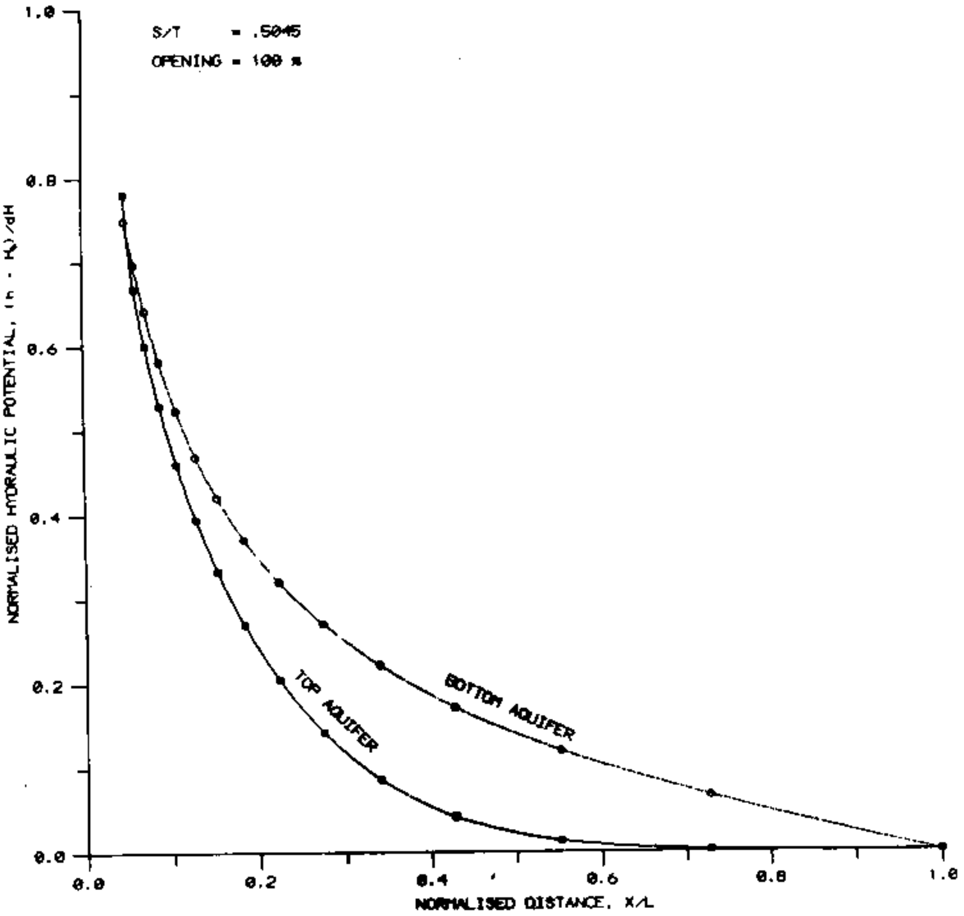


Fig. 19 Distribution of Hydraulic Potentials between the Centre and the Boundary of the aquifer system (vertical section) when Percentage Opening, O_P = 100% and Diffusivity, S/T = 0.5045

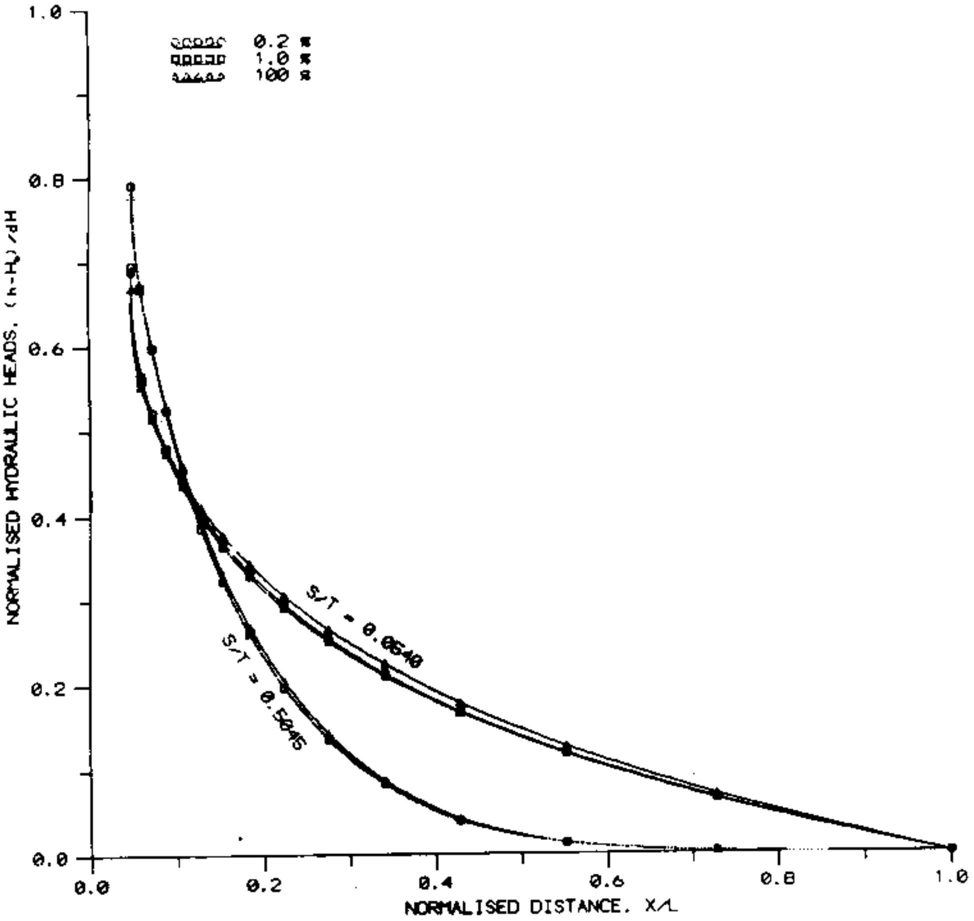


Fig. 20 Distribution of Hydraulic Potentials in the top aquifer between the Centre and the Boundary of the aquifer system (vertical section) for different Percentage Openings and Diffusivity values

0.5045 respectively. For smaller openings, a strong flow down to the bottom aquifer is indicated by the concentration of potential lines. It can be seen that as the percentage opening increases, the equipotentials are being more spread with larger slopes indicating more flow towards the boundaries.

Similarly, the equipotentials are drawn for S/T = 0.0540, 0.2162, 0.4 and 0.5045 respectively for percentage openings 30% and 100% respectively (Figs-10 & 11). Comparing the various plots, it may be seen that with diffusivity increasing the seepage to the bottom aquifer is also getting replenished.

Plots have been drawn between the normalised heads, (h - Hb)/dH with respect to the normalised distance, X/L from the source to the sink both for top and bottom aquifers for different S/T values and varying percentage openings, O_p. Figures 12, 13,14 &15 shows normalised potentials in the top as well as in the bottom aquifers for percentage openings 0.2%, 1%, 30% & 100% respectively when S/T = 0.0540. It may be noticed that when the percentage opening, O_p is small, the potential in the bottom aquifer lower than that in the top aquifer. However, for 30% opening the potential in the bottom aquifer exceeds that of the top aquifer after a certain distance from the source. Further, the potential is higher than that of the top aquifer throughout the system when the percentage opening becomes 100%. Similar plots have been made for a larger diffusivity value (S/T = 0.5045) also (Figs-16, 17, 18 & 19). Though the pattern remains the same, it can be seen that the exceedence of potential of bottom aquifer occurs even for small percentage openings, O_p.

Further analysis reveals that, in the top aquifer, the head distribution is invariant with respect to percentage openings, O_p for a specific S/T value (Fig-20). Nevertheless, for increased values of S/T, the rate of change of head in the top aquifer is steeper. This indicates that as S/T value increases the distance of influence of the source decreases. However, in the bottom aquifer, for a given diffusivity value the hydraulic potential

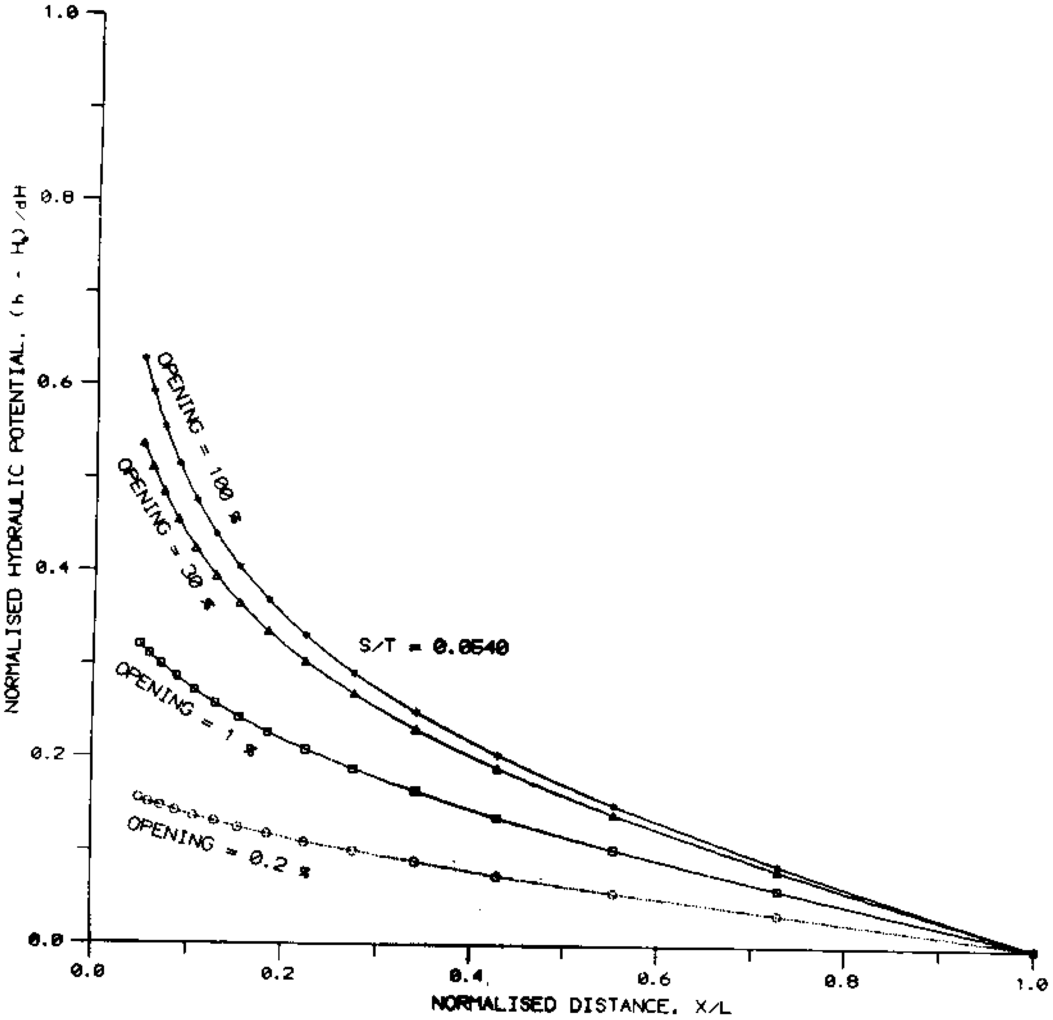
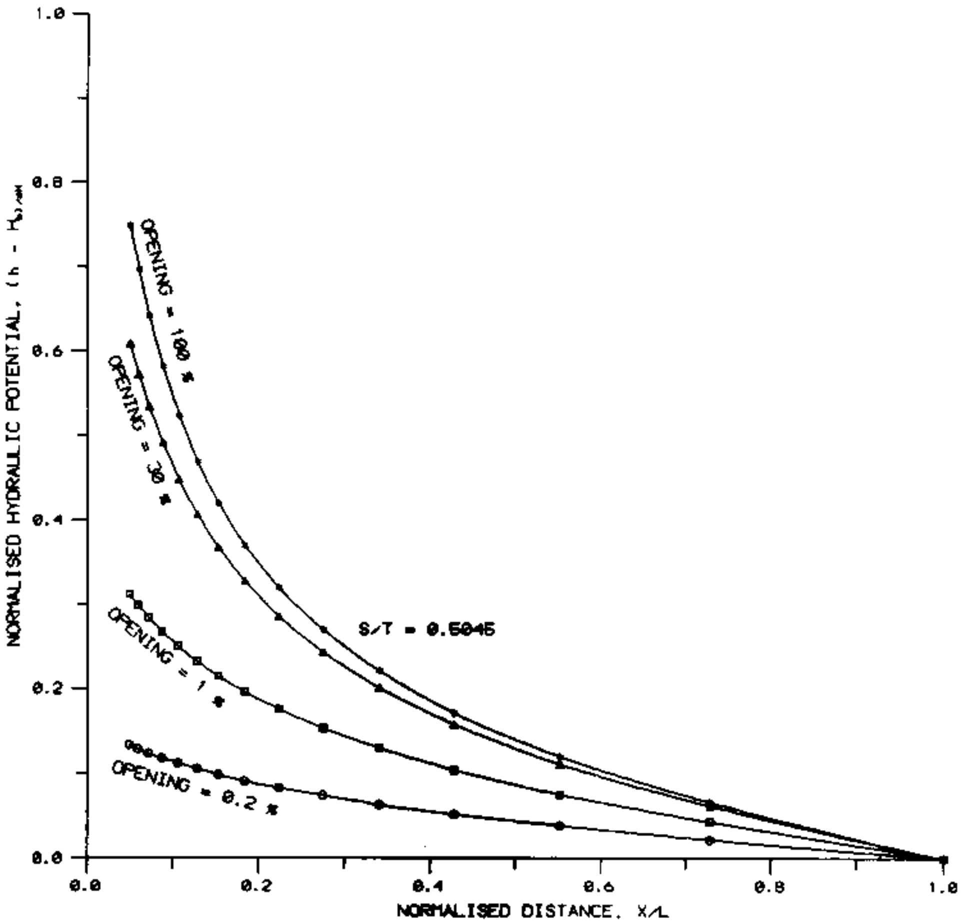


Fig. 21 Distribution of Hydraulic Potentials in the bottom aquifer between the Centre and the Boundary of the aquifer system (vertical section) for Diffusivity, S/T = 0.0540 and Percentage Openings, O_p = 0.2%, 1%, 30% & 100%



ig. 22 Distribution of Hydraulic Potentials in the bottom aquifer between the Centre and the Boundary of the aquifer system (vertical section) for Diffusivity, S/T = 0.5045 and Percentage Openings, O_P = 0.2%, 1%, 30% & 100%

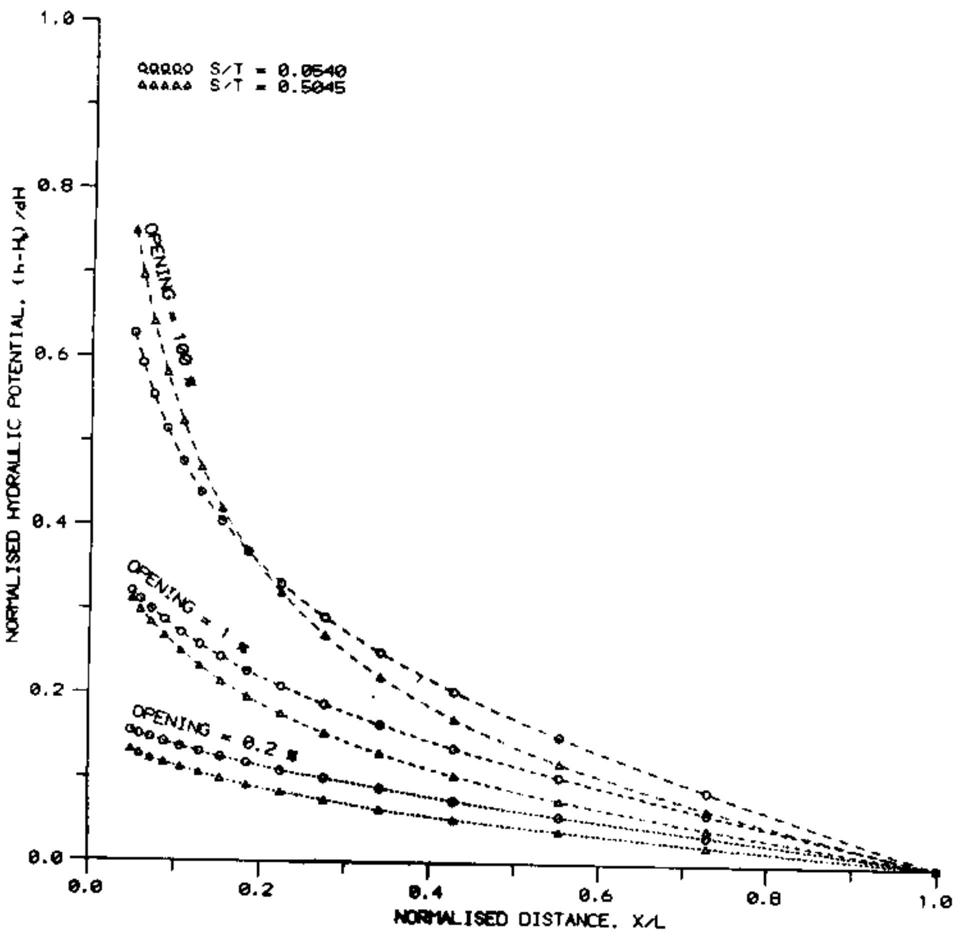


Fig. 23 Distribution of Hydraulic Potentials in the bottom aquifer between the Centre and the Boundary of the aquifer system (vertical section) for different Percentage Openings and Diffusivity values

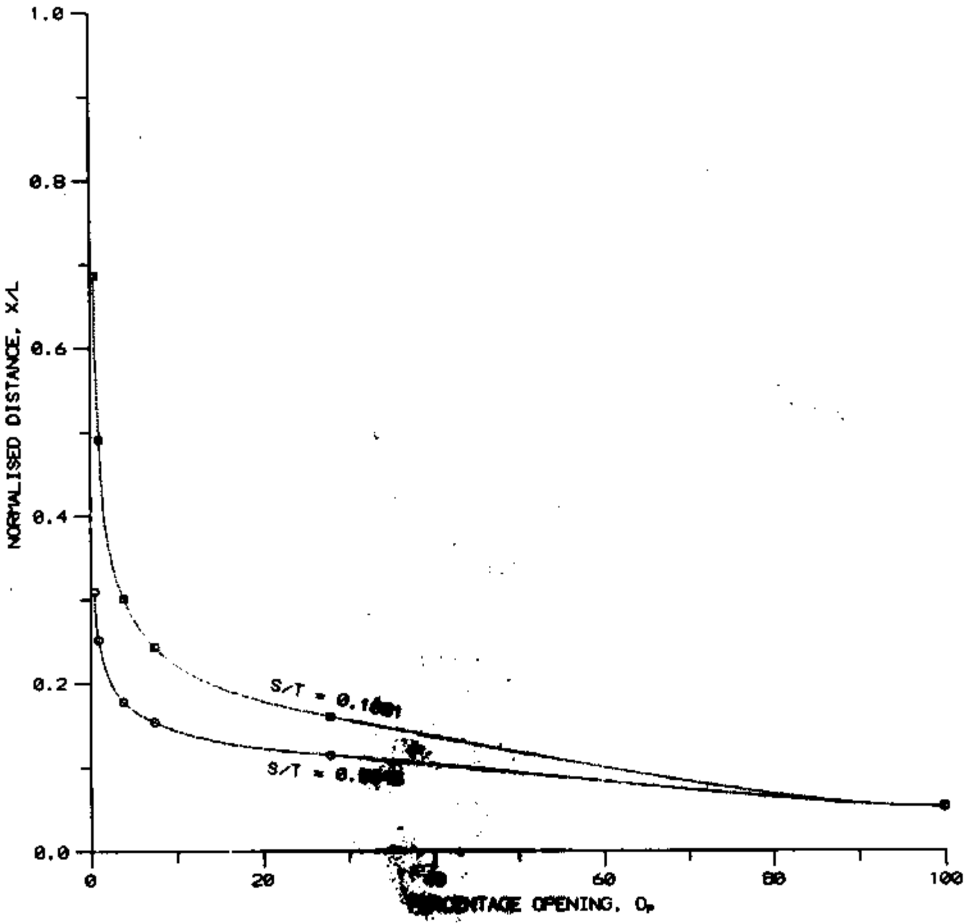


Fig. 24 Percentage Opening, O_p versus Reversal Points of Hydraulic Potentials

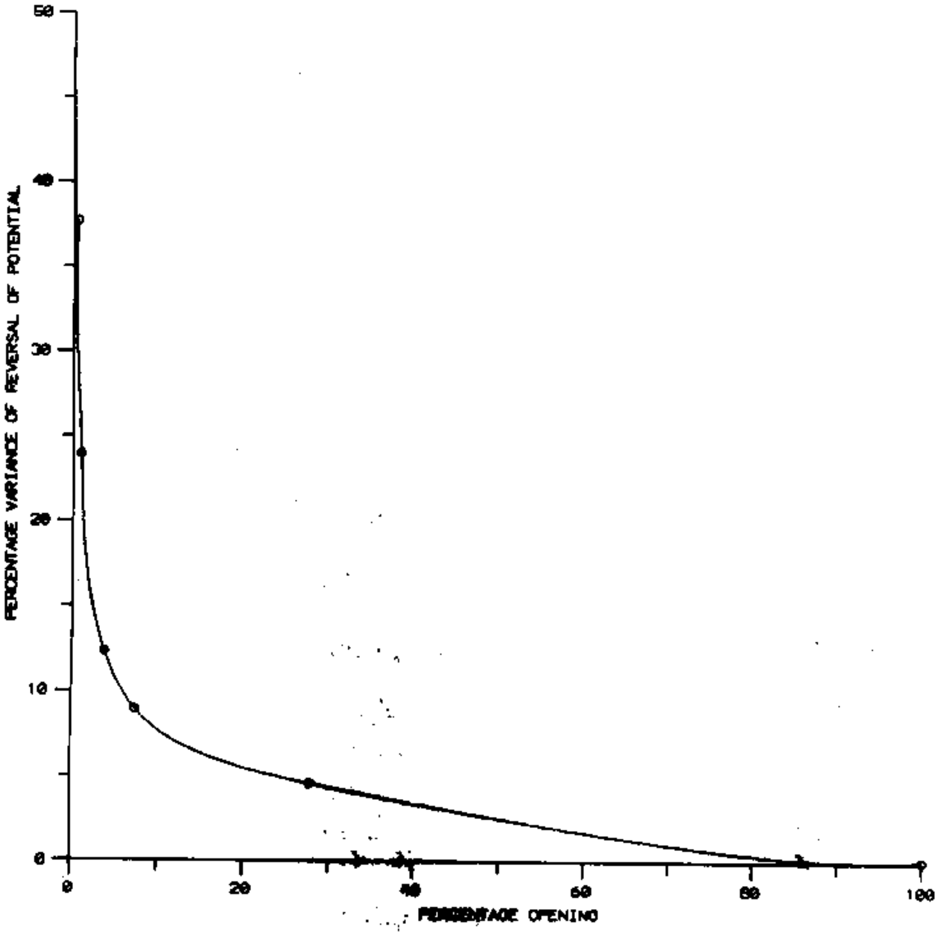


Fig. 25 Difference curve of Reversal Points of Hydraulic Potentials for two Diffusivity values S/T = 0.0540 & 0.5045

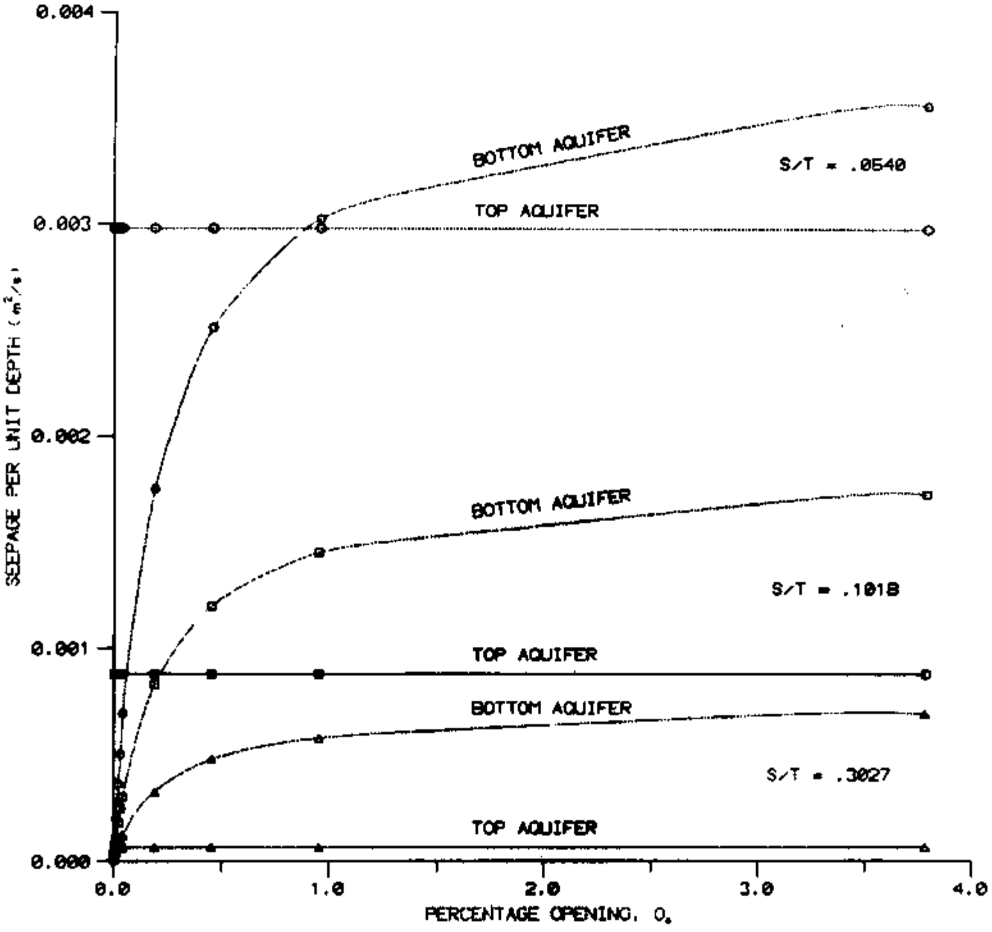


Fig. 26 Percentage Opening versus Seepage to the top as well as bottom aquifer respectively for different values of Diffusivity

is rising with increased dimension of the openings (Figs-21 & 22). Unlike the top aquifer, the percentage opening, O_p also affects the distribution of the potentials; larger the opening, steeper is the slope of head change (Fig-23).

In view of the discussion above, there exists a point, X_R between the source and the boundary at which the potentials are the same both in the bottom and top aquifers (vide Figs-12 to 19). With reference to this point, the bottom aquifer has lower potential towards the source-side and higher potential towards the sink-side. In other words, this is a point where reversal of potentials takes place between the top and bottom aquifers. But for the existence of the flow barrier separating the aquifer system into top and bottom aquifers, the direction of flow would have been reversed too. These points of reversal of potential vary with the degree of discontinuity in the aquitard as well as hydraulic diffusivity (S/T) as seen from the plots. Figure 24 is a plot of hydraulic potential reversal points vis-a-vis percentage openings for a small and a large S/T values. It is found that the reversal points are nearer to the source for a larger S/T value. However, when the opening is sufficiently large (say, 80%) the sensitivity with respect to S/T is vanished (Fig-24). This fact is expressed using the difference curve shown in figure 25.

The seepage quantities for both top and bottom aquifers have been computed for different percentage openings, O_p as well as S/T values (Fig-26). While top aquifer seems to receive a constant seepage irrespective of O_p, it is found to reduce with higher S/T values. The bottom aquifer has a varied seepage both with respect to O_p and S/T. This variation is significant for smaller percentage opening, O_p.

The fractional seepage to the bottom aquifer (F_{sb}) is plotted against S/T for various O_p (Fig-27). It is found that the contribution to the bottom layer (as fractional seepage) increases with increased values of S/T and O_p. But, even for very small O_p in the aquitard (say, 1%) the contribution of seepage to bottom aquifer is significantly high.

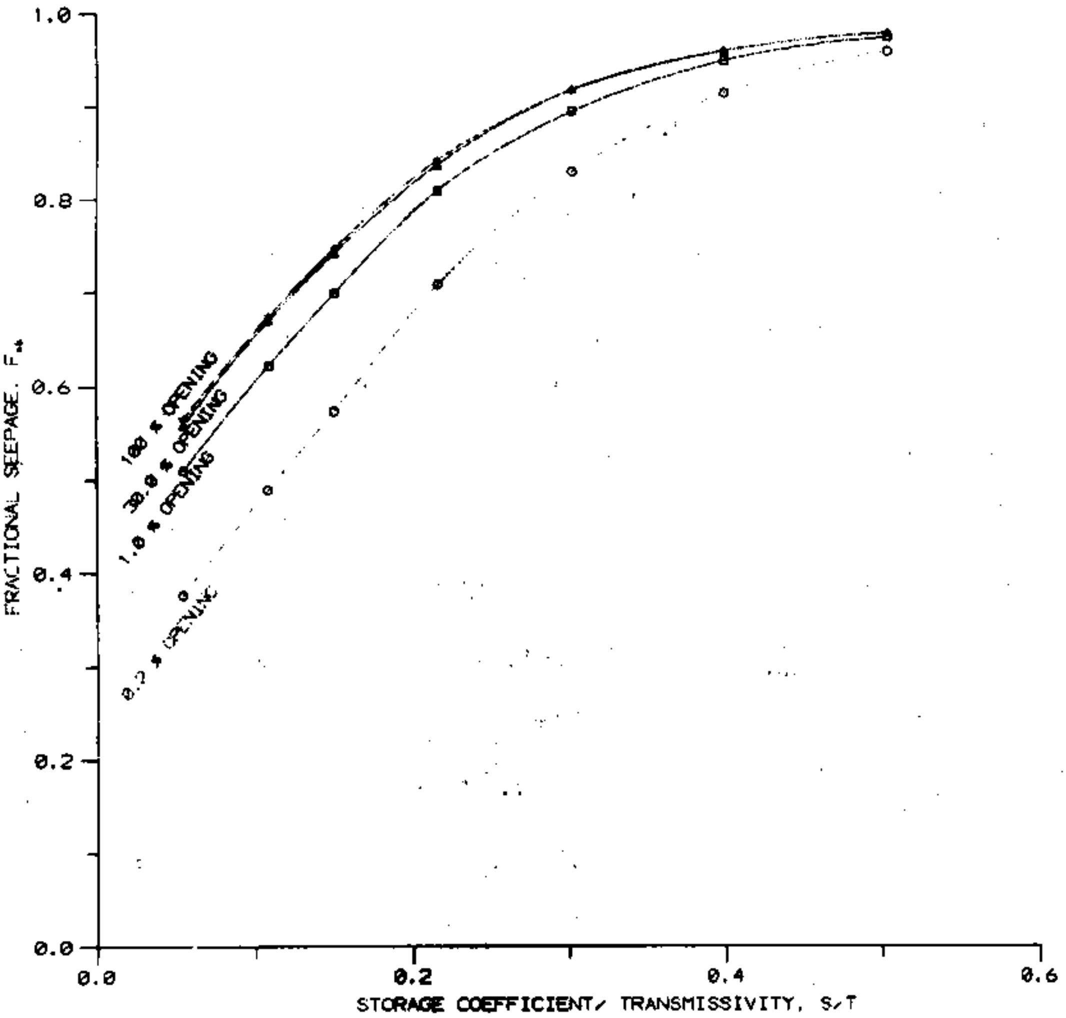


Fig. 27 Diffusivity, S/T versus Fractional Seepage, F_{sb} to the bottom aquifer for Percentage Openings, O_p = 0.2%, 1%, 30% & 100%

O_p greater than 30% have apparently little significance as far as the seepage is concerned. Also, as S/T increases the influence of O_p reduces on fractional seepage, F_{sb}. It is discernable that for S/T value of 0.5, the F_{sb} attains a near-maximum (about 0.95) indicating that the bottom aquifer receives most of the seepage. In other words, the recharge is predominantly to the bottom aquifer irrespective of the dimension of openings for large ratios of S/T.

The 100% opening curve almost matches with that of 30% opening. In other words a discontinuity of one third the dimensions of the source is sufficient to recharge the bottom confined aquifer. Larger openings that may not have any significant influence. It is interesting to observe that a very small percentage opening like 0.2% induces considerable seepage down to the bottom aquifer reflected by the small difference between the curves for 30% and 0.2%. This difference is even diminishing with lager values of S/T. Apparently, even a very small opening can attract tremendous flow through it.

By way of this fact, minute openings developed in the confining bed or cut-off wall of storage tanks/ reservoirs can drain the water away. On the other hand, in order to replenish an aquifer below a flow barrier in an artificially recharged area, a minute discontinuity may be created in the barrier.

5.0 CONCLUSION

The influence of a discontinuous aquitard on the seepage from a recharge source in a multi-layered aquifer system, with the prescribed hydrogeological set-up, has been subjected to investigation.

The analysis brought forth the following important observations/ results:

(a) So long as the ratio S/T is kept constant the fractional seepage, F_{ib} to the aquifer system is invariant to changes in S or T values.

(b) For the top aquifer, the discontinuity in the aquitard has little relevance to the head distribution except very near to the source; also, the distance of influence of the source is reduced as the ratio S/T increases.

(c) For the bottom aquifer, the head distribution is influenced by both S/T ratio as well as discontinuity in the aquitard;

(d) Even for a very small percentage opening of the order of 1%, the contribution of seepage to the bottom aquifer is significantly high.

(e) Further, the seepage is predominantly to the bottom aquifer irrespective of the dimension of discontinuity in the aquitard for large ratios of S/T.

The study, therefore, suggests that the parameter S/T determines the quantum of recharge rather than independent values of S and T. Also, even a minor fracture in the aquitard can induce significant seepage to the second aquifer.

6.0 REMARKS

The influence of discontinuous aquitard on the seepage from a recharge source in a multi-layered aquifer system has been subjected to investigation. The study brought forth interesting results. Further studies are envisaged by incorporating aspects like: eccentricity of the discontinuities; positioning of the flow barrier; a range of values for head-causing flow; changing boundary conditions; changing aspect ratios of the system; non-uniform/ transient recharge from the source.

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