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AUSTRALIAN WATER RESOURCES COUNCIL

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HYDRAULIC DESIGN DATA FOR WATER WELLS IN UNCONSOLIDATED SEDIMENTS

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Preface

The work reported in this publication forms the final report on the Australian Water Resources Council Research Project 71/25, Drilling and Development Problems in Sediments. Associated work on the project, dealing with drilling mud invasion of unconsolidated aquifer materials, and the effects of near-well permeability variation on well performance are reported seperately in Australian Water Resources Council Technical Papers Numbers 17 and 18.

This publication sets out hydraulic design data for water wells in unconsolidated sediments. It is intended to supplement the information already available to groundwater hydrologists and is not intended to be a complete treatise on well design. Information of a practical nature on well construction, equipment and completion techniques is not included.

The graphs and tables provided have been extracted from the Ph.D. thesis submitted to the University of New South Wales by R.J. Cox. The research leading to the publication was carried out at the Water Research Laboratory of the University of New South Wales. It involved theoretical, numerical and experimental investigations over a period of seven years. The research was funded through Projects 68/8 and 71/25 of the Australian Water Resources Council and a scholarship from the Commonwealth Scientific and Industrial Research Organisation. The authors are grateful for the assistance provided.

The assistance of members of staff of the Water Research Laboratory is also gratefully acknowledged. Particular thanks are due to another member of the research team, Pongsarl Huyakorn, whose contributions have been published in other reports referred to in this publication. The authors wish to express their gratitude to members of the project reference panel for practical guidance during the course of the project. Membership of the panel was as follows:-

Mr W.H. Williamson (Chairman)	-	Water Resources Commission, New South Wales.
Mr W.B. Lane	-	Irrigation and Water Supply Commission, Queensland.
Mr A.A. Webster	-	State Rivers and Water Supply Commission, Victoria.
Mr R.R. Hancock	-	Department of Mines, South Australia.
Mr D.L. Rowston	-	Geological Survey, Western Australia.
Mr H.F. Eggington	-	Water Resources Branch, Department of Northern Territory.

Dr J. Gordon-Smith, Department of Environment, Housing and Community Development, Canberra, acted as secretary to the reference panel.

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a) - coefficients in Forcheimer equation $I = aV+bV^2$ (may be subscripted
b) - to refer to a particular zone of an inhomogeneous aquifer)

h - hydraulic head above base of aquifer

h_f - free surface height at well in unconfined aquifer

h_o - hydraulic head at radius of influence

h_w - water level in well

I - hydraulic gradient

K - hydraulic conductivity (may be subscripted to refer to a particular zone of an inhomogeneous aquifer)

l - length along screen

l_b - height of open end of large diameter well above base of aquifer

l_s - length of screen

m - aquifer thickness (may be subscripted to refer to the thickness of a particular layer in an inhomogeneous aquifer)

Q - well discharge

r - radius from centre of well (may be subscripted to refer to a particular zone of an inhomogeneous aquifer)

r_o - radius of influence

r_w - radius of well

s - drawdown in aquifer $(h_o - h)$

s_w - drawdown in well $(h_o - h_w)$

T - transmissivity of aquifer

V - flow velocity

V_{cr} - velocity at upper limit of validity of Darcy equation

1. Introduction

Rational design of a water well[1] to be constructed at a given point in an aquifer necessitates prediction of the drawdown-discharge relationship for each type of construction and geometrical configuration under consideration. This relationship will depend on the well diameter, the type, lengths and positions of screens [2], the thickness and hydraulic properties of the aquifer as a whole within the zone of influence of the well and, in particular, the hydraulic properties of the aquifer material close to the well. The latter properties may differ markedly from the "average" properties of the entire aquifer because of natural inhomogeneity or the effects of well construction or development on a zone which may extend several well diameters beyond the screen.

Once it is possible to predict the drawdown-discharge relationship over the range of variables involved, alternative designs may be compared and the optimum selected, subject to the constraints imposed on the designer. Selection of the optimal design should normally be based on economic considerations. Constraints may include the capabilities of drilling equipment, the range of well components obtainable and available power supplies for pumps.

In cases where well fields are being designed, interference effects between wells may result in the optimal design differing from that for a single well.

When the performances of single wells are being compared it is necessary in most cases only to consider the steady-state drawdown for a given discharge since pumping periods are usually long enough to allow the relatively rapid changes of water level in the well during early pumping times to be neglected. The design data presented later are thus for steady-state conditions.

This publication is aimed at providing practising groundwater hydrologists with more complete information than has been available to date on the effects of the design variables on the drawdown-discharge relationship for a range of conditions considered likely to be encountered in practice. The range has been selected after examination of records of wells constructed in unconsolidated sedimentary aquifers in the Eastern Australian States.

The data provided have been obtained by applying finite element digital computer programs to analyse flow conditions in close proximity to

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[1] The term "well" is used to denote a vertical cylindrical hole in the ground used to extract or inject water regardless of diameter or method of construction. It thus encompasses the commonly used terms "borehole" and "water bore".

[2] The term "screen" is used to refer to a portion of the well casing made porous in some manner to allow the entry of water from the aquifer.

wells. Information which comes from this analysis includes the well drawdown-discharge relationship and the distribution of head and velocity throughout the aquifer. Only the well drawdown is treated in detail here. Velocities at the well screen are considered from the point of view of particle movement and head loss through the screen. Some typical distributions of head are also given for general information. More complete data can be obtained from Cox (1976).

The finite element analysis and computer programs have been verified as far as possible by comparing output with known analytical solutions and electrical analogue and experimental tank results. The programs allow not only complex well geometries to be studied but account for the possibility of non-Darcy flow developing near the well. Source and object checks and listings are available for those who wish to extend the range of data given here or solve for more complex aquifer conditions.

2. Design Variables

2.1 General

The variables which affect the drawdown-discharge relationship for a well may be divided into those which are fixed once the particular site in the aquifer has been selected and those which the designer has control of. They might be referred to as aquifer properties and well variables respectively. The two groups are not completely independent, however. For instance the hydraulic characteristics of the aquifer material immediately surrounding the well may be altered during drilling and development to a degree which may depend on such factors as the well geometry and extent and type of screens and gravel packs.

2.2 Aquifer Properties

2.2.1 Type, Extent and Thickness of Aquifer

The type, extent and thickness m of the aquifer must be determined by an adequate program of drilling and geophysical exploration before the behaviour of wells within the aquifer can be predicted.

The aquifer thickness at the site of the well has a greater effect on well drawdown than the thickness at more remote points. It should thus be the value used when entering the graphs and tables which follow. Should the aquifer thickness vary rapidly near the well it would be necessary to modify the computer programs previously mentioned to solve the special case involved.

2.2.2 Flow Equations

The basic equation used in this work to describe the relationship between hydraulic gradient I and velocity V in the flow region is the Forchheimer equation

$$I = aV + bV^2$$

where a and b are the linear and non-linear constants respectively. For low flow velocities the equation may be replaced by

$$I = aV$$

or the conventional Darcy equation form

$$V = KI$$

where $K = 1/a$ is the hydraulic conductivity. For higher velocities the bV^2 term must be retained and the flow becomes significantly non-linear.

In flow towards a well, significant deviations from Darcy's law will occur only in a zone near the well. The radius of this zone will normally not exceed several metres.

For a given aquifer, one pair of constants has been found to give a sufficiently accurate fit to experimental velocity-hydraulic gradient results over the range of velocities likely to be met in well flow problems (Cox (1976)). All the presented data are based on the use of a single pair of a and b values in any homogeneous zone within the aquifer. An alternative approach (Huyakorn (1974)) is to divide the flow region into two zones, an inner one near the well in which velocities are high enough to induce non-Darcy flow and in which the Forchheimer equation is used and an outer zone in which velocities are low enough for Darcy's law to be used. The latter approach requires a limiting velocity V_{cr} to be specified directly or through a limiting Reynolds number. There is no significant difference between the results obtained by the two methods provided appropriate hydraulic constants are selected to fit the equations to the known permeability data of the aquifer material. There is, however, a practical disadvantage in using this type of two-regime approach with a limiting velocity in the analysis of flow to wells as an additional dimensionless term is introduced.

2.2.3 Overall Transmissivity and Storage

Once a site is chosen for a well the transmissivity and storage within the area of influence become fixed. The values to be used in the design are preferably obtained by pump testing a trial hole on the site but frequently must be inferred from the results of testing at adjacent sites or from experience of similar aquifers. Since pseudo-steady flow is assumed in comparing well performances the transmissivity is the basic piece of information required for design. The transmissivity T must be converted to hydraulic conductivity $K = \frac{T}{m}$ or the the Forchheimer linear constant $a = \frac{1}{K} = \frac{m}{T}$ to allow entry to the graphs which follow.

2.2.4 Hydraulic Characteristics of Aquifer Material Close to the Well

Since the permeability of the material close to the well has a disproportionately large effect on well drawdown it is important that it be assessed as accurately as possible. It is in this zone that high head losses associated with non-Darcy flow may occur and the effects of partial penetration and screening are concentrated. A survey of the degree of variability of the aquifer, geophysical logging of a trial hole on the site and detailed pump testing of this hole with appropriate close observation holes and analytical techniques (Dudgeon et al (1973), Huyakorn (1974)) will all contribute to an increase in accuracy. Pump testing may disclose local aquifer inhomogeneity and/or non-linear flow characteristics if the results are subjected to careful analysis. The design information required and which may be obtained by these methods are the Forchheimer equation constants a and b and the radial extent of any zone of material whose characteristics must be considered different from those of the aquifer as a whole.

The possible effects of drilling and development on the properties of the aquifer close to the well should be given careful consideration when the predicted performances of trial designs are being compared. Reference should be made to Dudgeon and Cox (1975) and Dudgeon and Huyakorn (1975) for information on this subject.

In many cases the cost of determining near-well aquifer characteristics may not be warranted. It will then be necessary to estimate them from experience or published data and normally available information such as drilling logs and samples. The non-linear constant b in the Forchheimer equation may be estimated from the results of laboratory experiments on typical aquifer materials. Cox (1976) suggests the relationship

$$a = 2.5b^{4/3} \quad \text{(cm, sec. units only)}$$

which yields the dimensionless ratio

$$\frac{b}{a^2} = 0.5\,K^{1.25} \quad \text{(cm, sec. units only)}$$

required to enter the well performance data graphs. In most cases, a considerable error in the estimate of the ratio b/a^2 will not materially affect the choice of an optimal design.

2.3 Well Variables

2.3.1 Well Geometry

Within the limits of practical construction techniques and available materials the designer has complete control over such variables as well radius, screen length and position and characteristics of gravel packs if provided.

The symbols used for variables are defined in Figures 1(a) and 1(b)

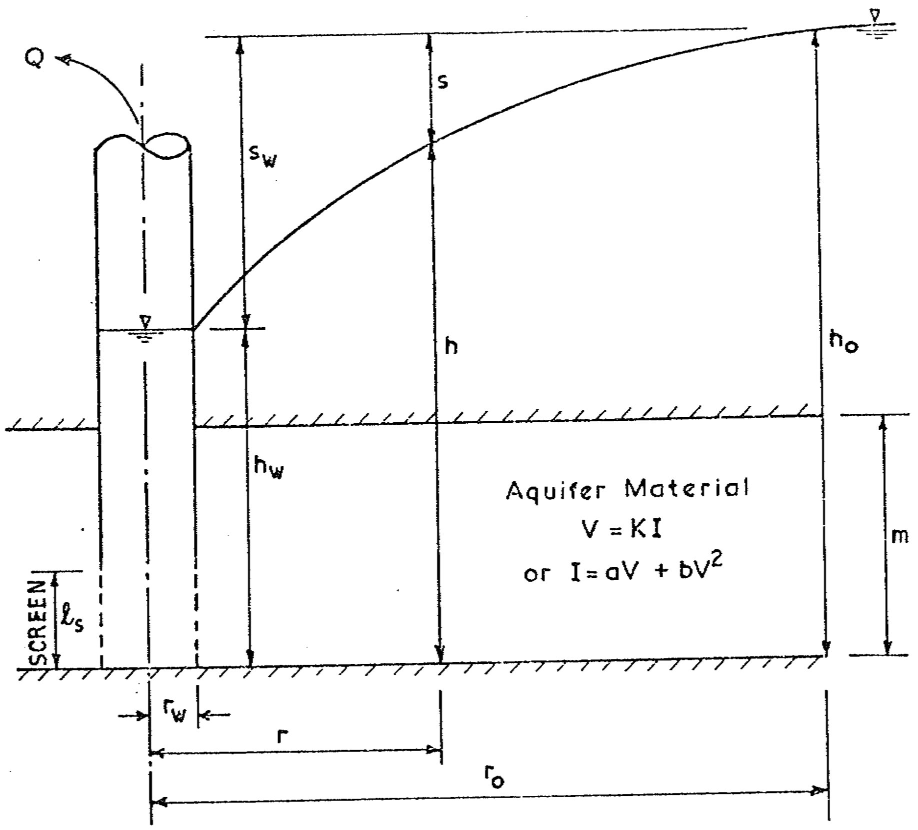


FIGURE 1(a): PARTIALLY SCREENED WELL IN A CONFINED AQUIFER.

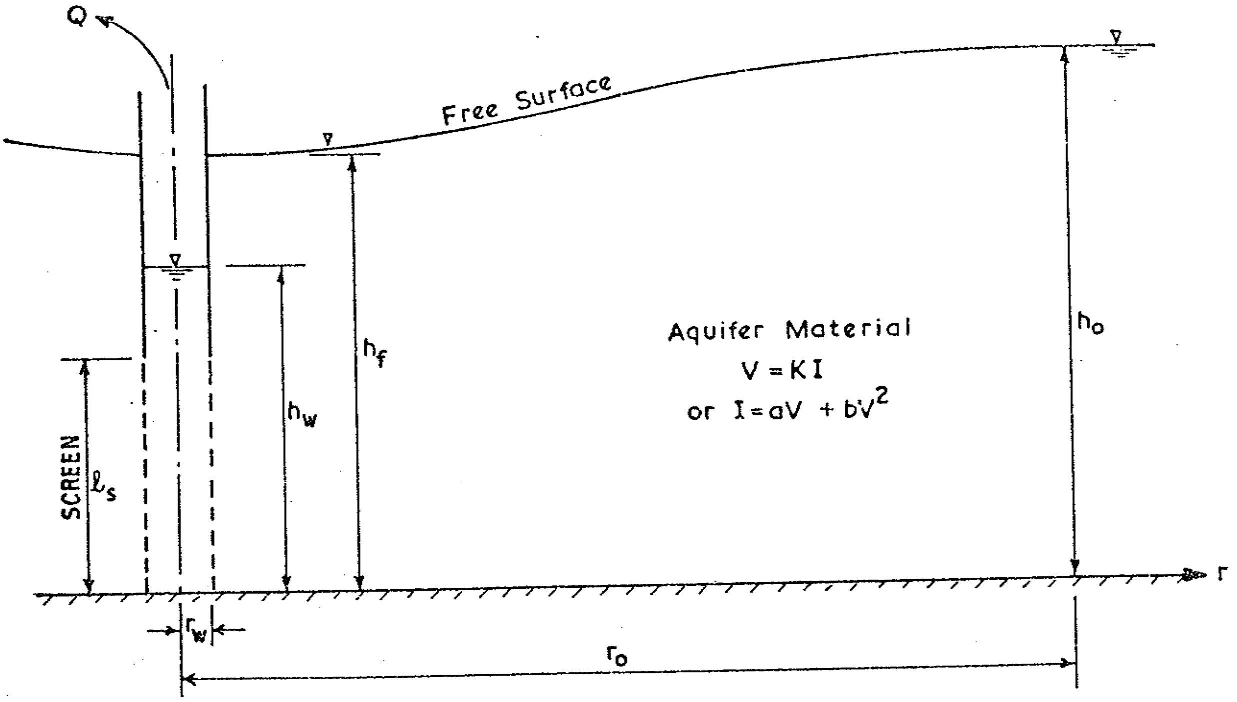


FIGURE 1(b): PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER.

for confined and unconfined aquifers respectively.

2.3.2 Radius of Influence

The radius of influence r_o of a well depends not only on the aquifer characteristics but also on the discharge and time. A value must be selected before the well performance data provided can be used. Experience has shown that for wells in unconsolidated sediments the radius of influence commonly lies between 1,000 and 5,000 metres for confined aquifers and 100 and 500 metres for unconfined aquifers. Outside the radius of influence the effect of normal pumping is insignificant.

It is important to note that even though the choice of a radius of influence affects the predicted drawdown-discharge relationship it has little effect on the relative performance of different designs and thus on the selection of the optimum.

3. Prediction of the Effects of Aquifer and Well Variables on Well Performance

3.1 General

There are four basic methods the designer may use to predict the well drawdown-discharge relationship. They are:-

(a) Use of available published analytical solutions for the simpler well flow problems, for instance wholly Darcy flow to a fully penetrating well in a homogeneous confined aquifer (Thiem Equation).

(b) Use of graphs and tables drawn up in dimensionless form from the results obtained by solving commonly met flow cases. The data supplied in this publication are presented in this form. For aquifer and well configurations not covered it would be possible for a designer to prepare similar dimensionless charts using the computer programs referred to in (c). For complex problems the large number of variables involved makes this approach impractical as a very large number of graphs would have to be prepared. It would generally be less costly to solve a more restricted set of particular problems pertinent to the job in hand.

(c) Individual numerical solution of specific problems using computer programs such as those used by Cox (1976) or those presented by Huyakorn and Dudgeon (1974). As mentioned in 2.2.2 the former adopts a single Forchheimer relationship for the flow equation while the latter use a two-regime (Darcy and Forchheimer) approach (Huyakorn (1974)). The results are not significantly different.

This approach is only feasible where adequate computer facilities are available. It would normally be resorted to only where complex aquifers or well geometry occurred or where variables fell beyond the range of reasonable extrapolation of the graphs and tables already available.

(d) Physical and Analogue Modelling

The use of any but the simplest form of physical (e.g. sand tank) or analogue (e.g. electrical) model of a well-aquifer system is usually confined to laboratories specialising in groundwater hydraulics. Except in special circumstances the average designer will not have access to or need to use the facilities which are necessary. There may be cases where such modelling will provide the most economical method of predicting well performance but with the continual improvement in numerical prediction techniques this becomes less and less likely.

3.2 Subdivision of Problem Types

The conventional division into confined and unconfined aquifers has been adopted in setting out the design data although the numerical methods used to produce the graphs and tables allow semi-confined and semi-unconfined cases to be treated. It should be noted that in the case of unconfined aquifers the effect of the unsaturated zone has been neglected. Since the flow contribution from this zone is small it may safely be neglected when water supply wells are being designed. However, the zone must be taken into account when land drainage wells are being considered.

4. Wells in Confined Aquifers

4.1 Non-Dimensional Groupings of Variables

All design graphs for wells in confined aquifers are presented in terms of the dimensionless groups $\frac{Q}{Q_T}, \frac{m}{r_w}, \frac{r_o}{m}, \frac{l_s}{m}, \frac{b s_w}{a^2 r_w}$.

The discharge Q_T with which the predicted well discharge is compared is the Darcy flow discharge to a fully penetrating and screened well, all other conditions being identical. Q_T is given by the Thiem Equation $Q_T = \frac{2\pi K m s_w}{\ln(\frac{r_o}{r_w})}$. Other variables have been defined previously in Figure 1(a).

4.2 Homogeneous Aquifer, Single Screen

4.2.1 Basic Discharge Data

Figures 2 to 25 give the basic discharge data obtained from the computer programs for a well drawing water from a single screen in a homogeneous aquifer. The screen may be either at the top or bottom of the aquifer.

4.2.2 Use of Basic Graphs

When using the graphs provided, designers should keep in mind that non-Darcy flow will not normally occur beyond a radius of several metres from the well. Beyond this limit, which varies with the ratio $\frac{b}{a^2}$ and the well geometry and drawdown, well flow equations based on Darcy's law

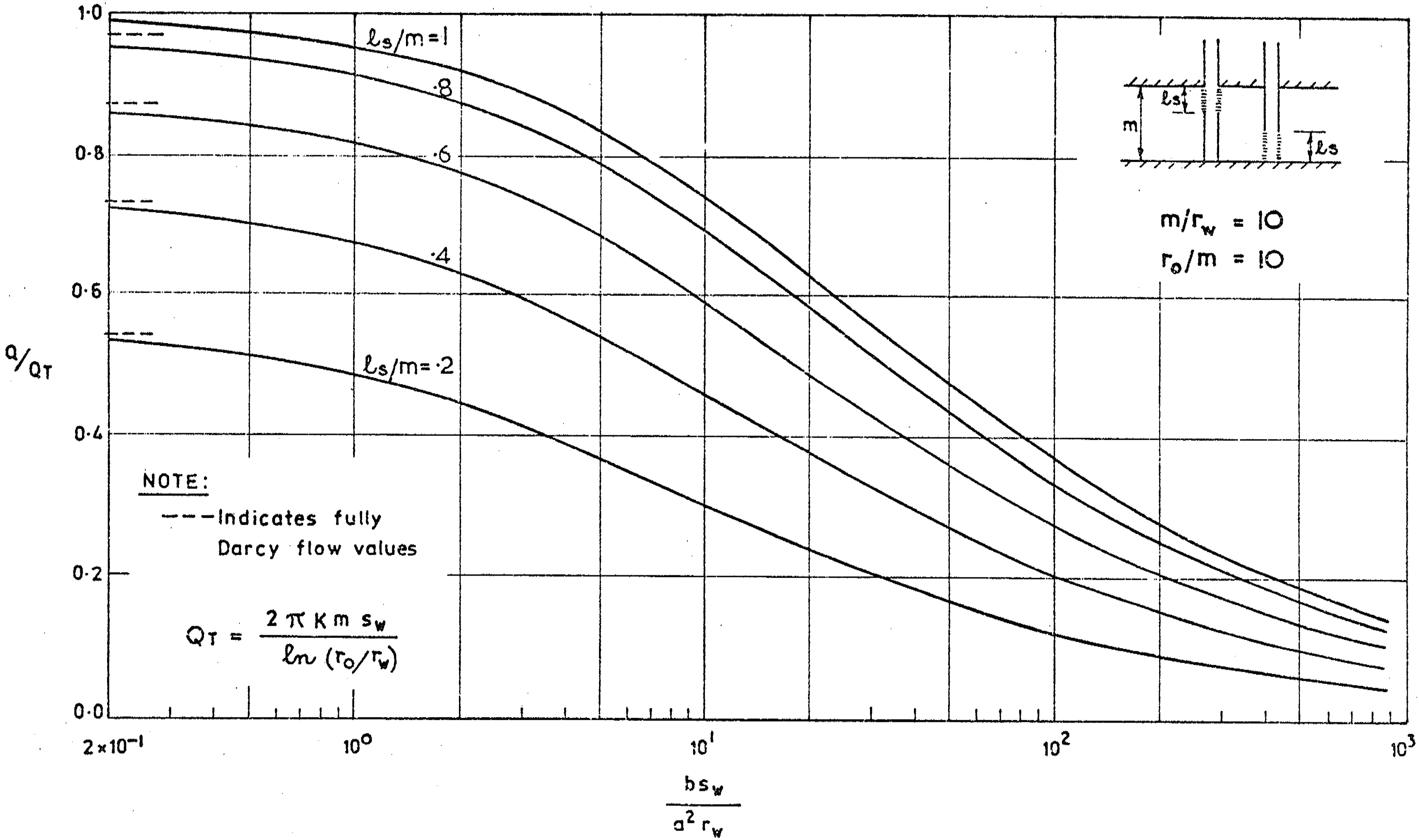
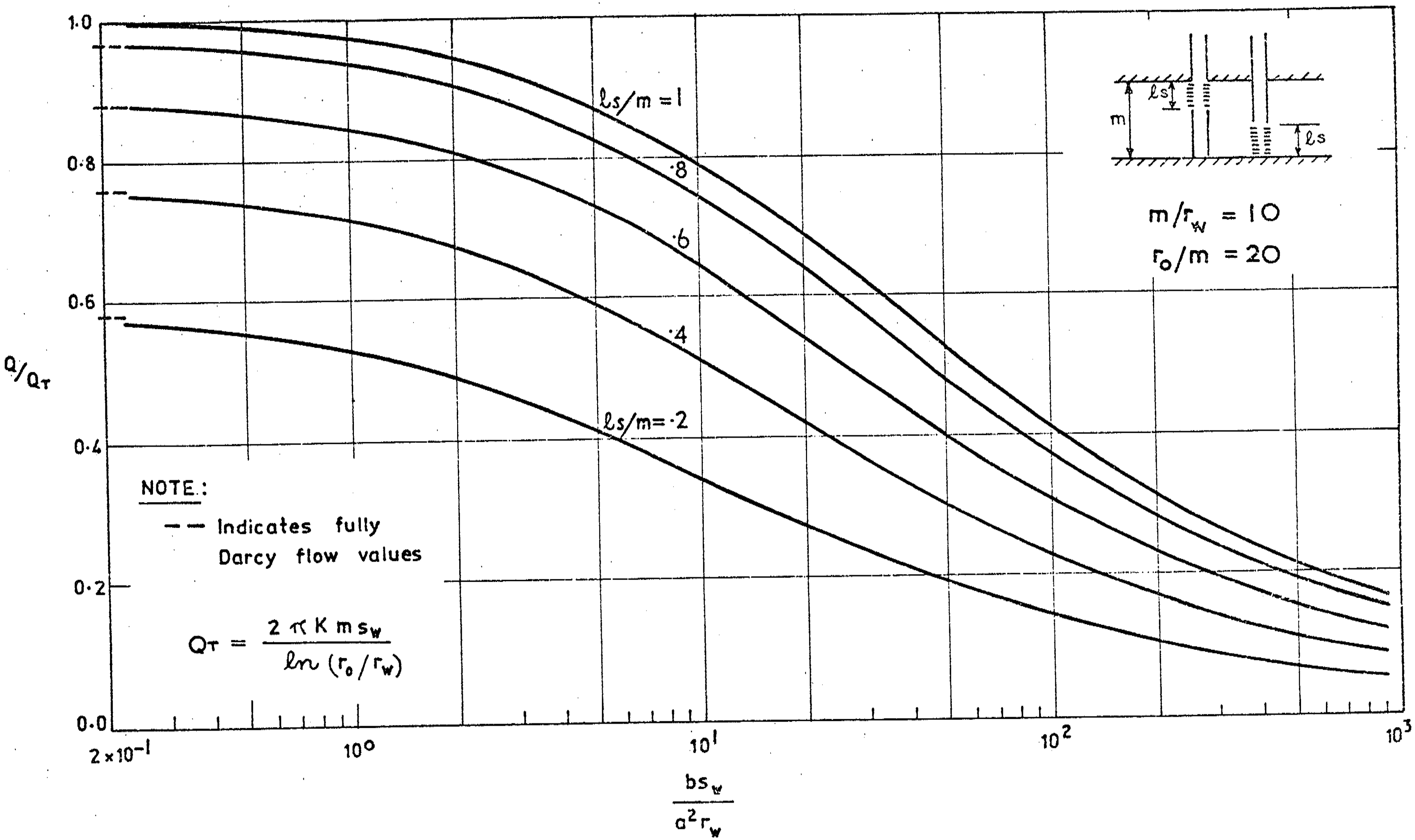


FIGURE 2: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER



NOTE:
-- Indicates fully Darcy flow values

$$Q_T = \frac{2\pi K m s_w}{\ln(r_o/r_w)}$$

FIGURE 3: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

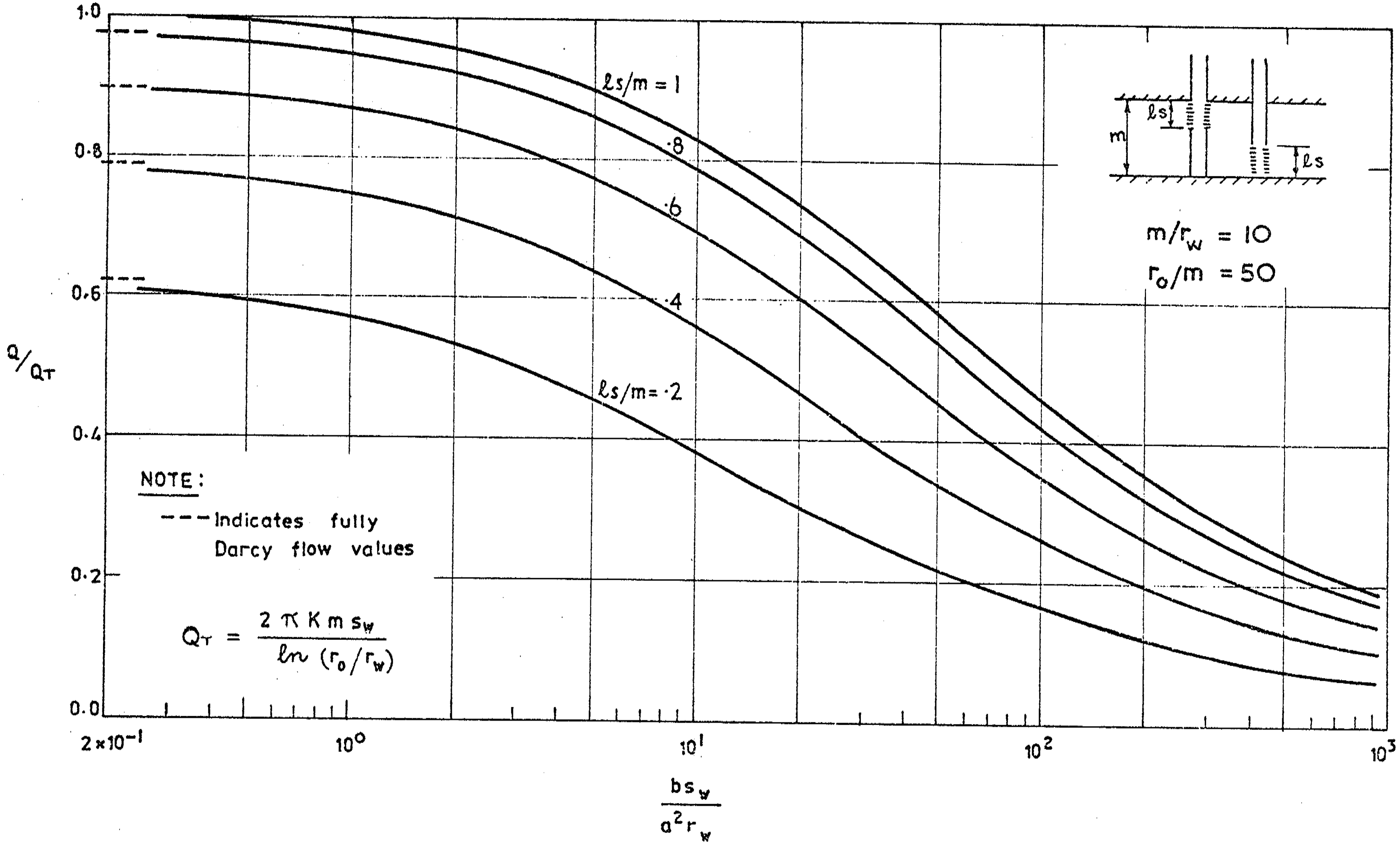


FIGURE 4: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN - DISCHARGE RELATIONSHIP. CONFINED AQUIFER

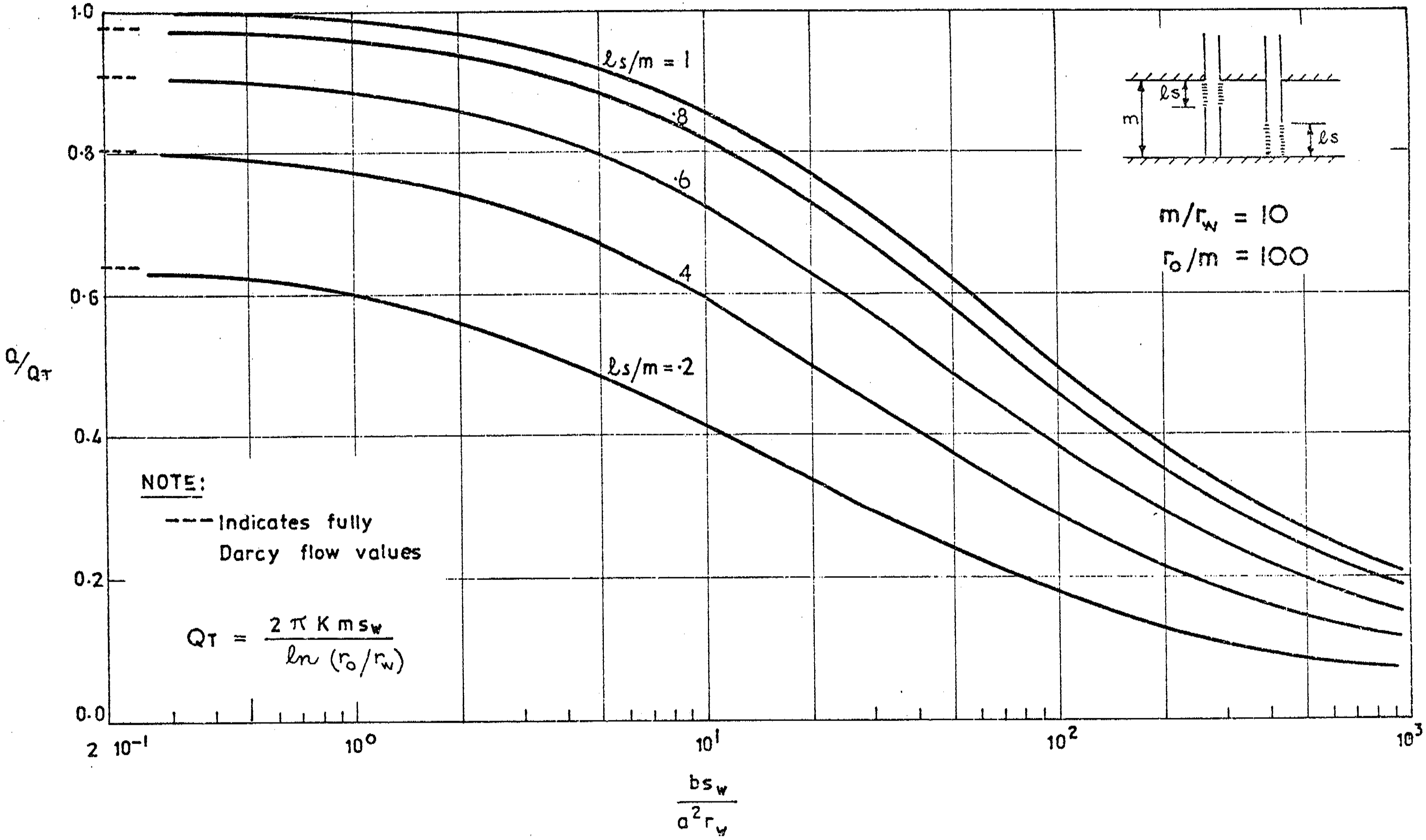


FIGURE 5: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

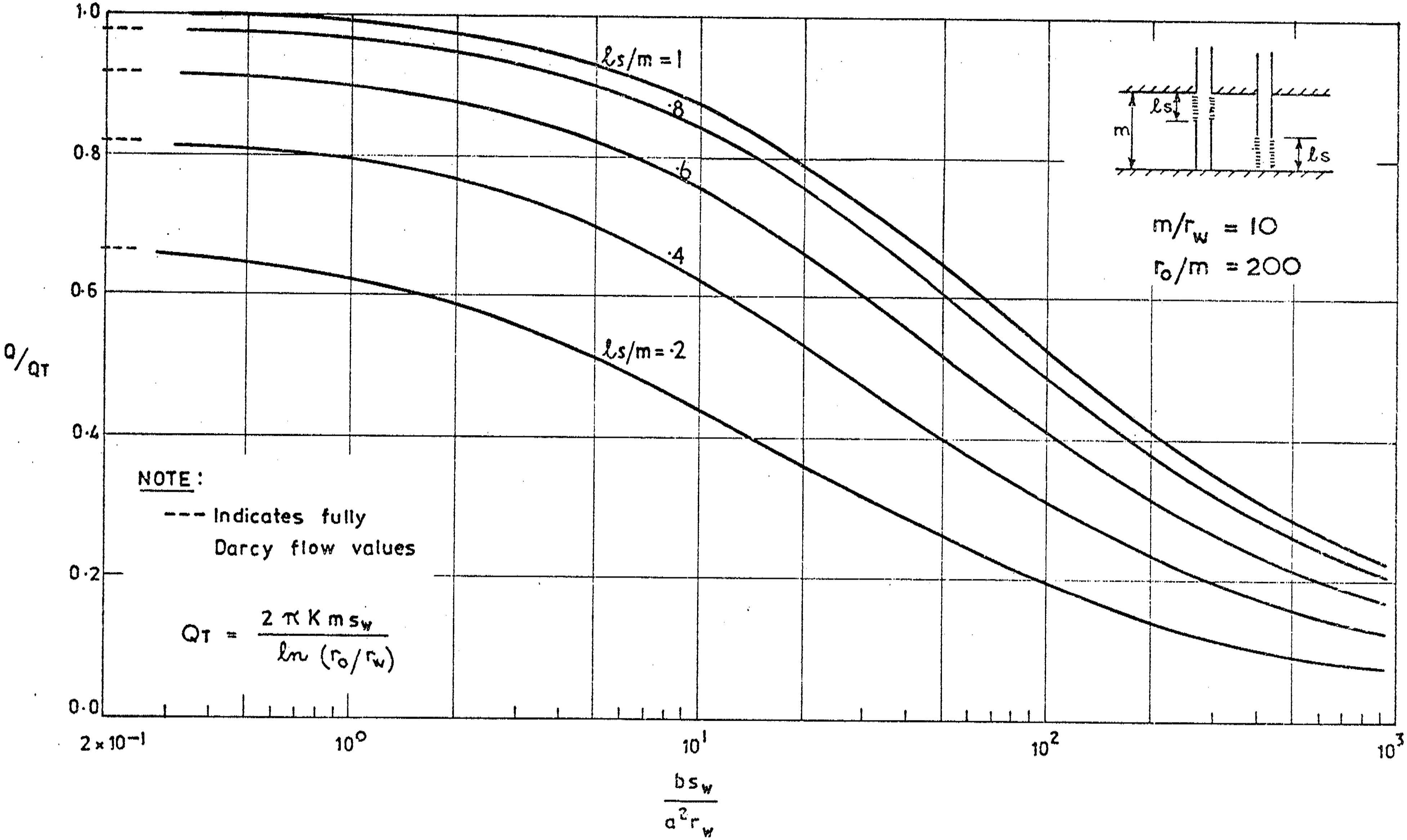


FIGURE 6: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

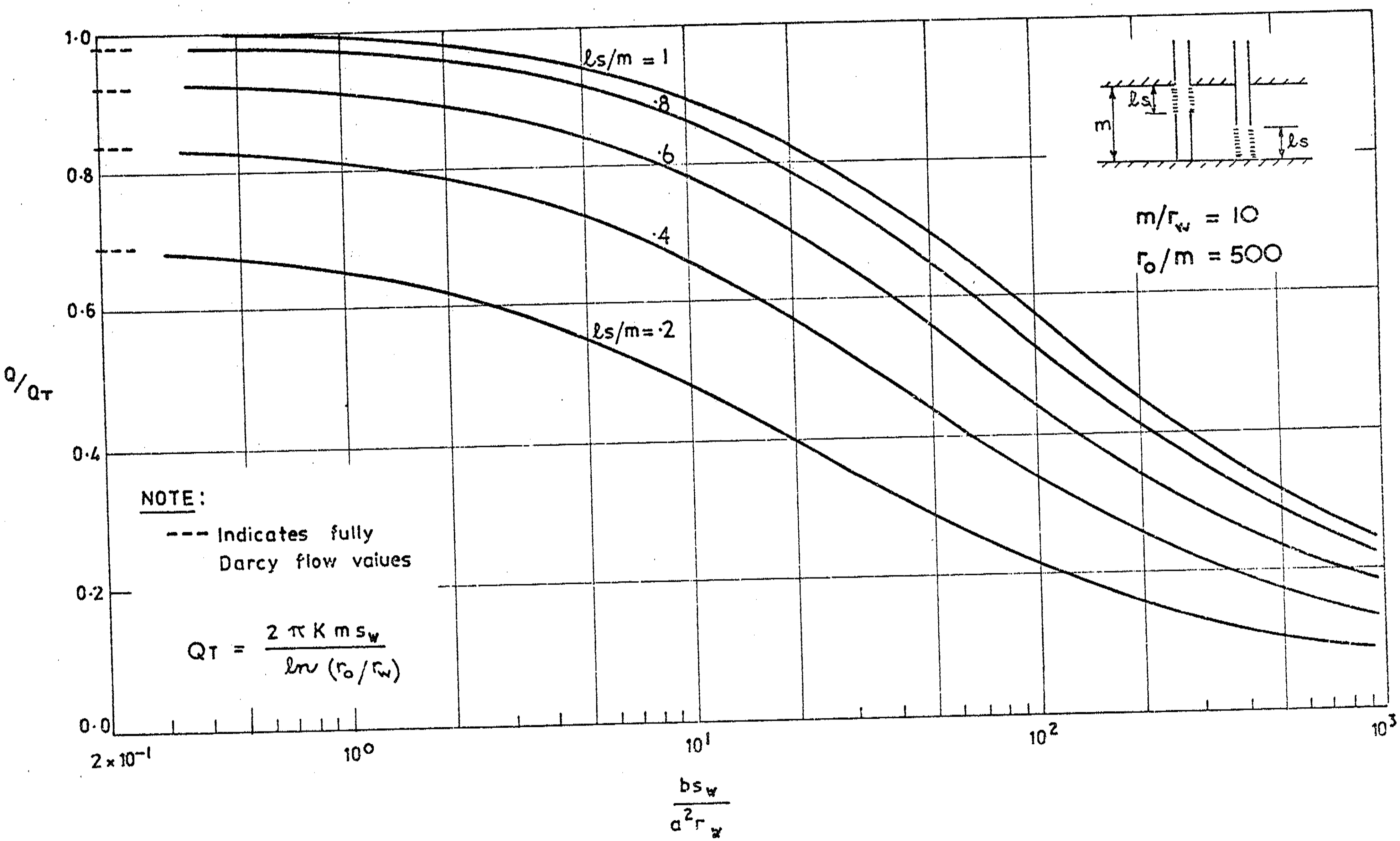


FIGURE 7: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

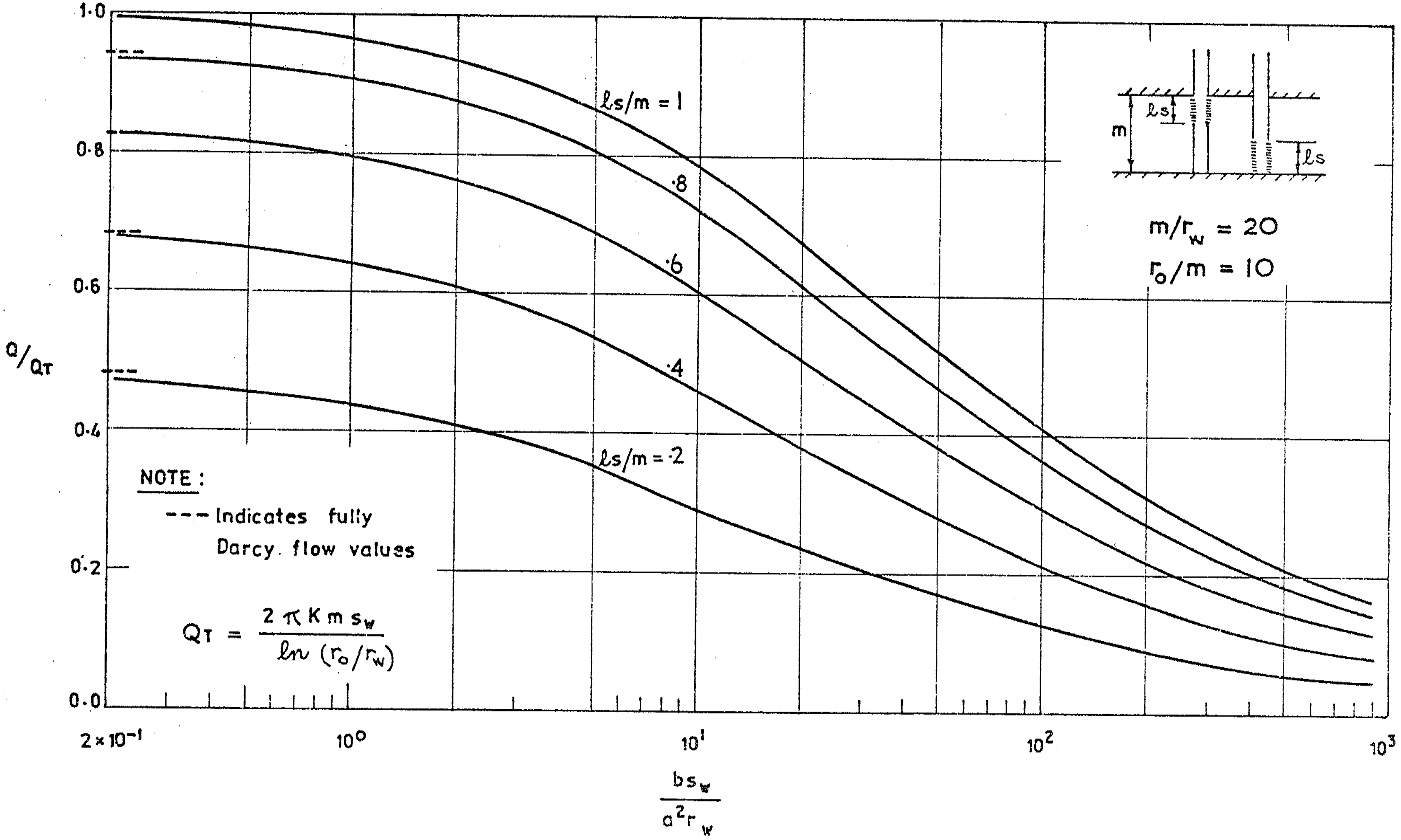


FIGURE 8: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

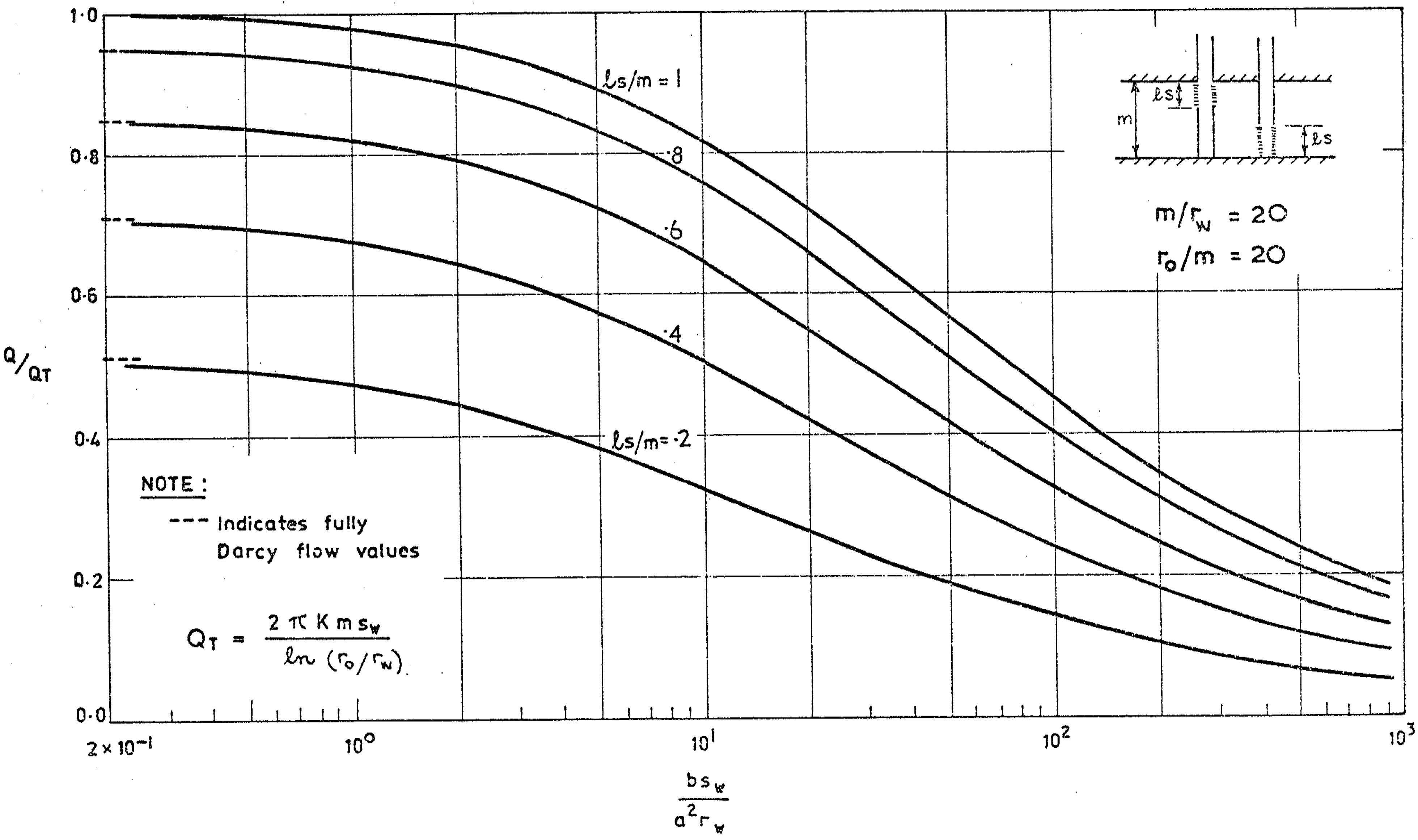


FIGURE 9: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

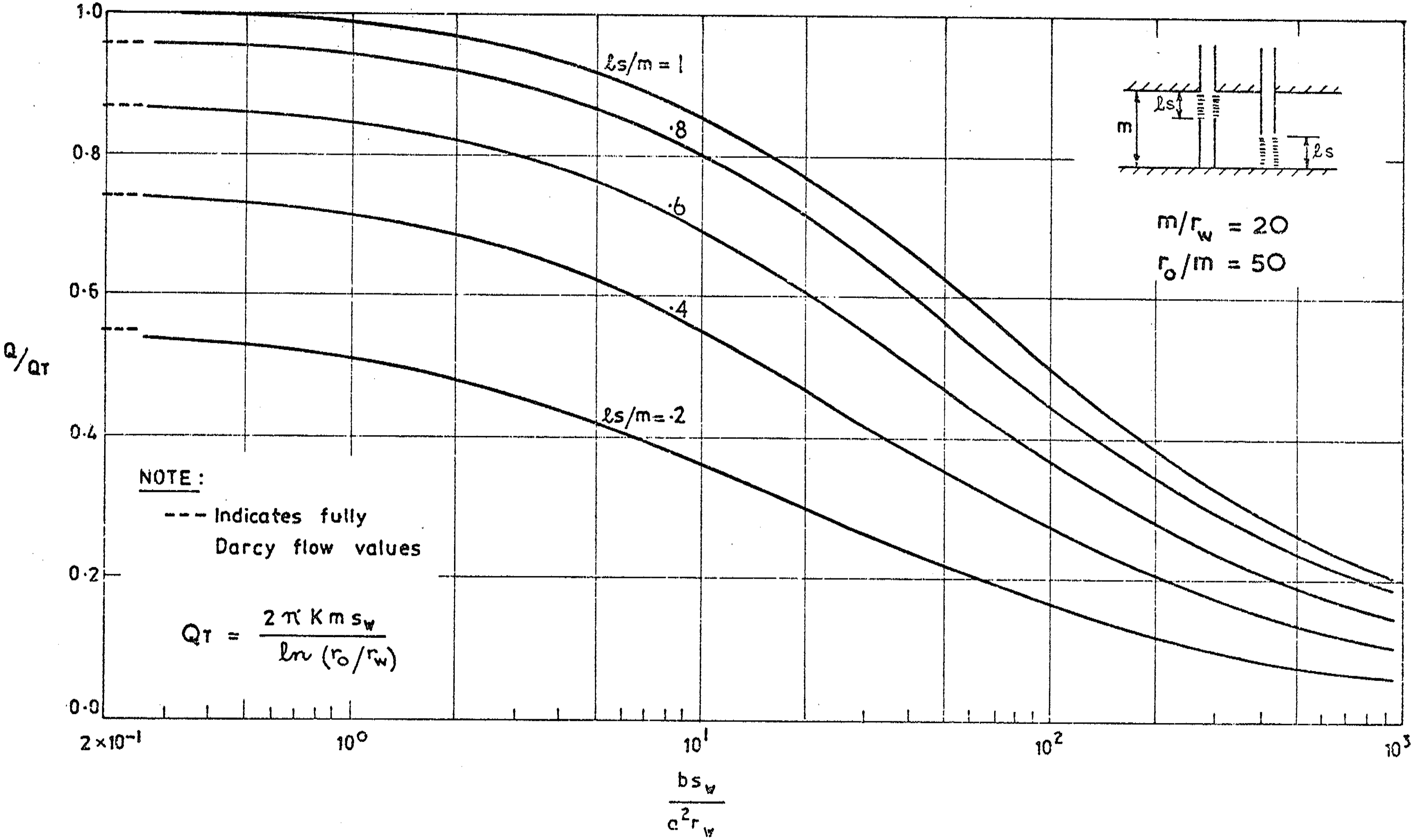
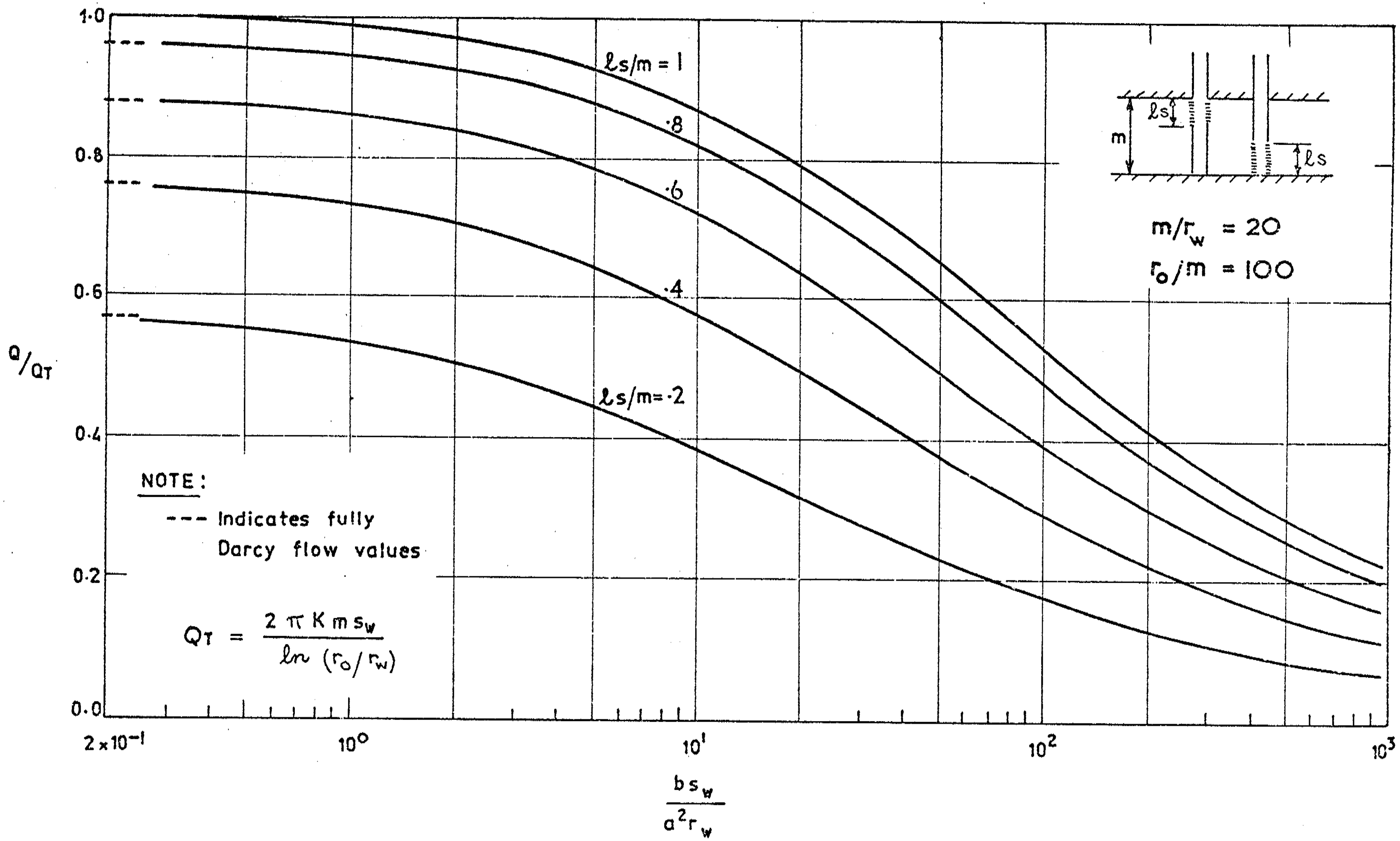


FIGURE 10: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER



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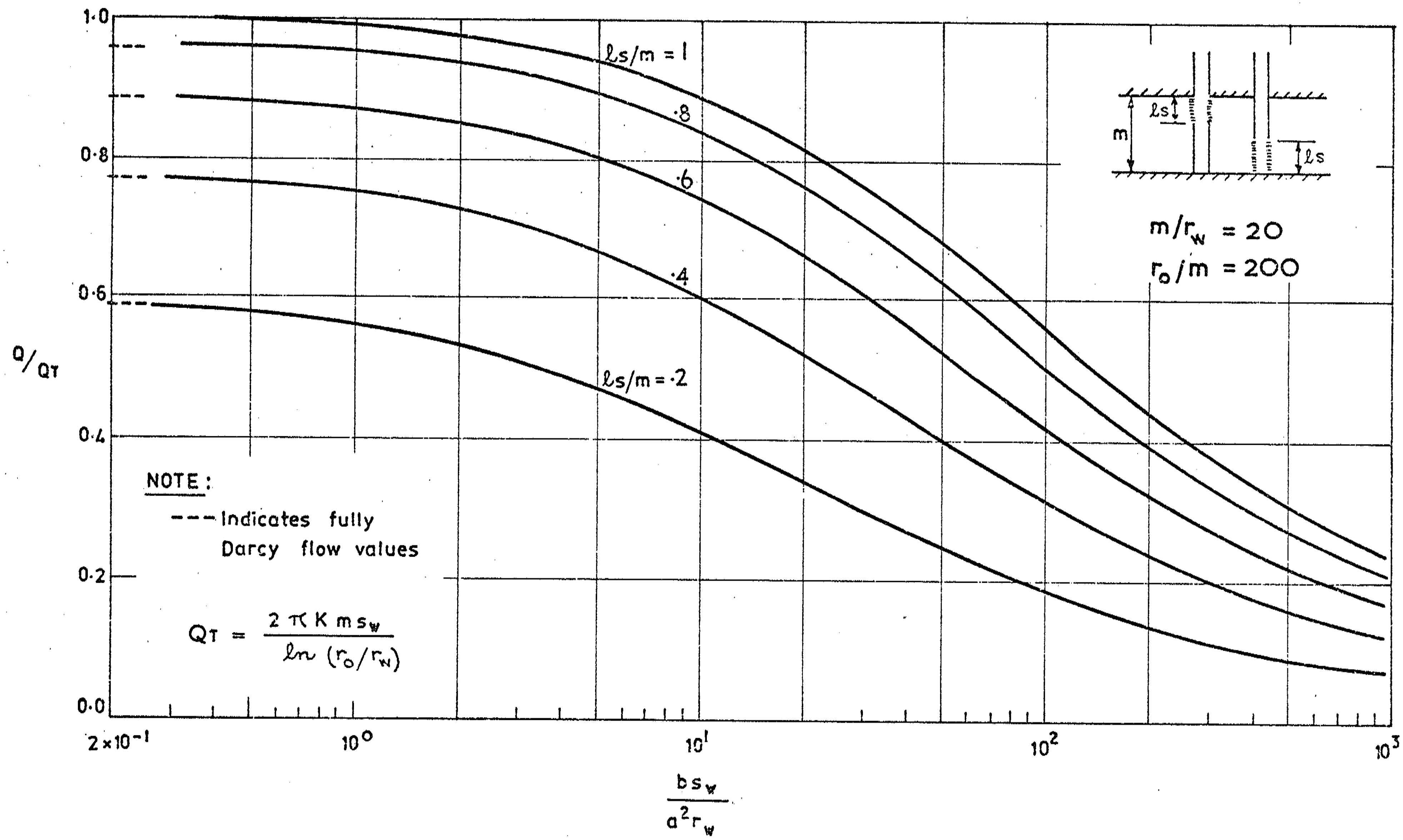


FIGURE 12: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

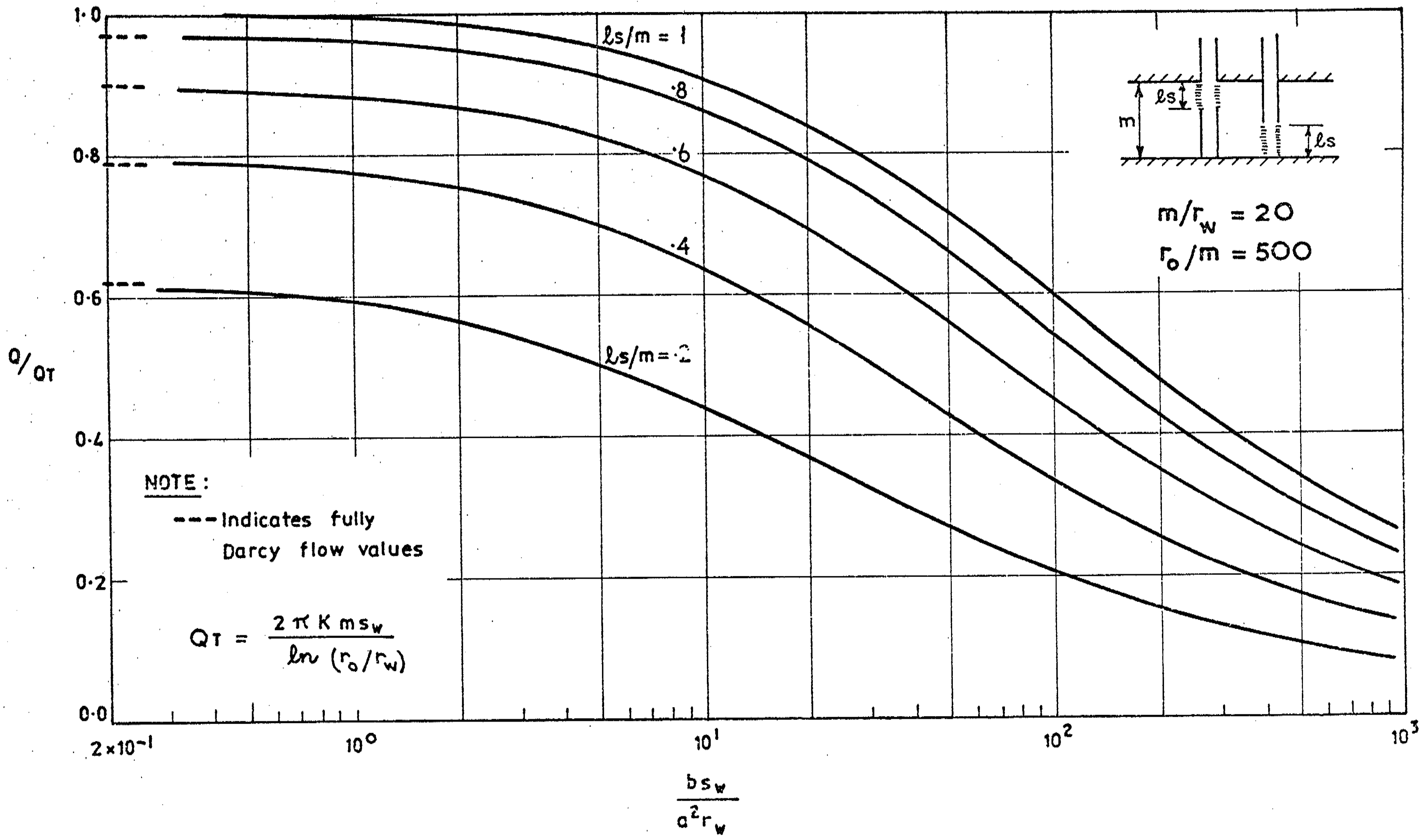


FIGURE 13: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

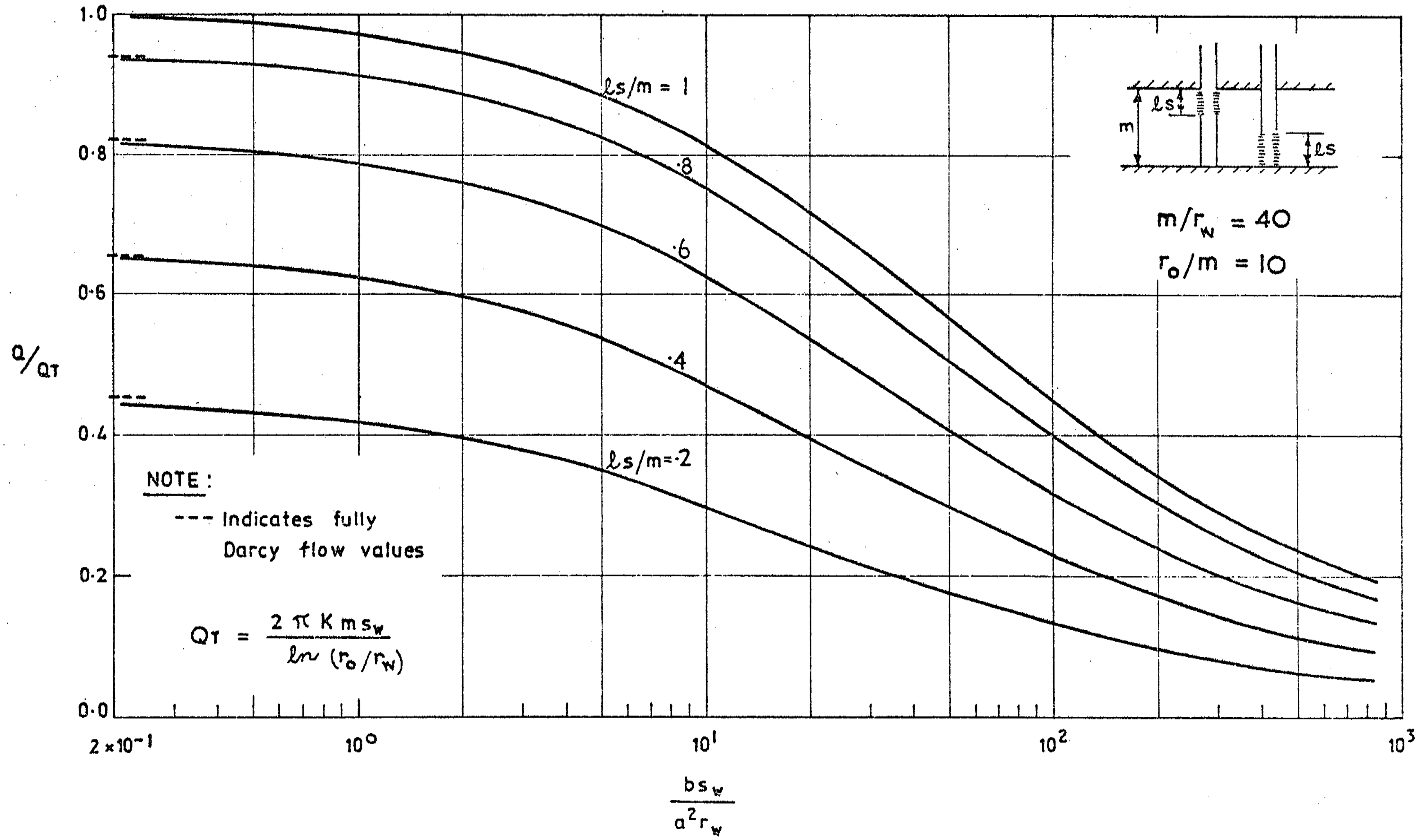


FIGURE 14: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

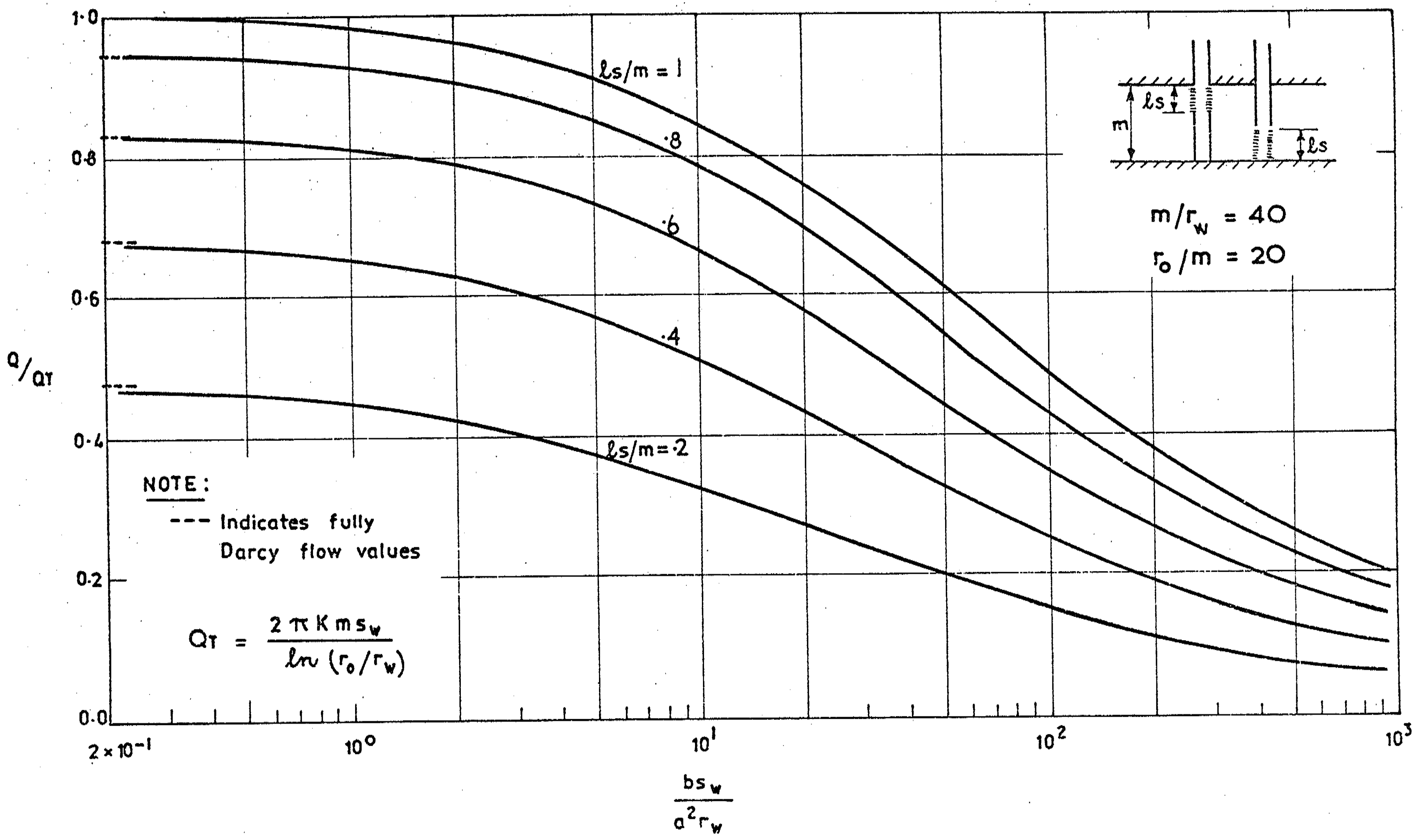


FIGURE 15: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

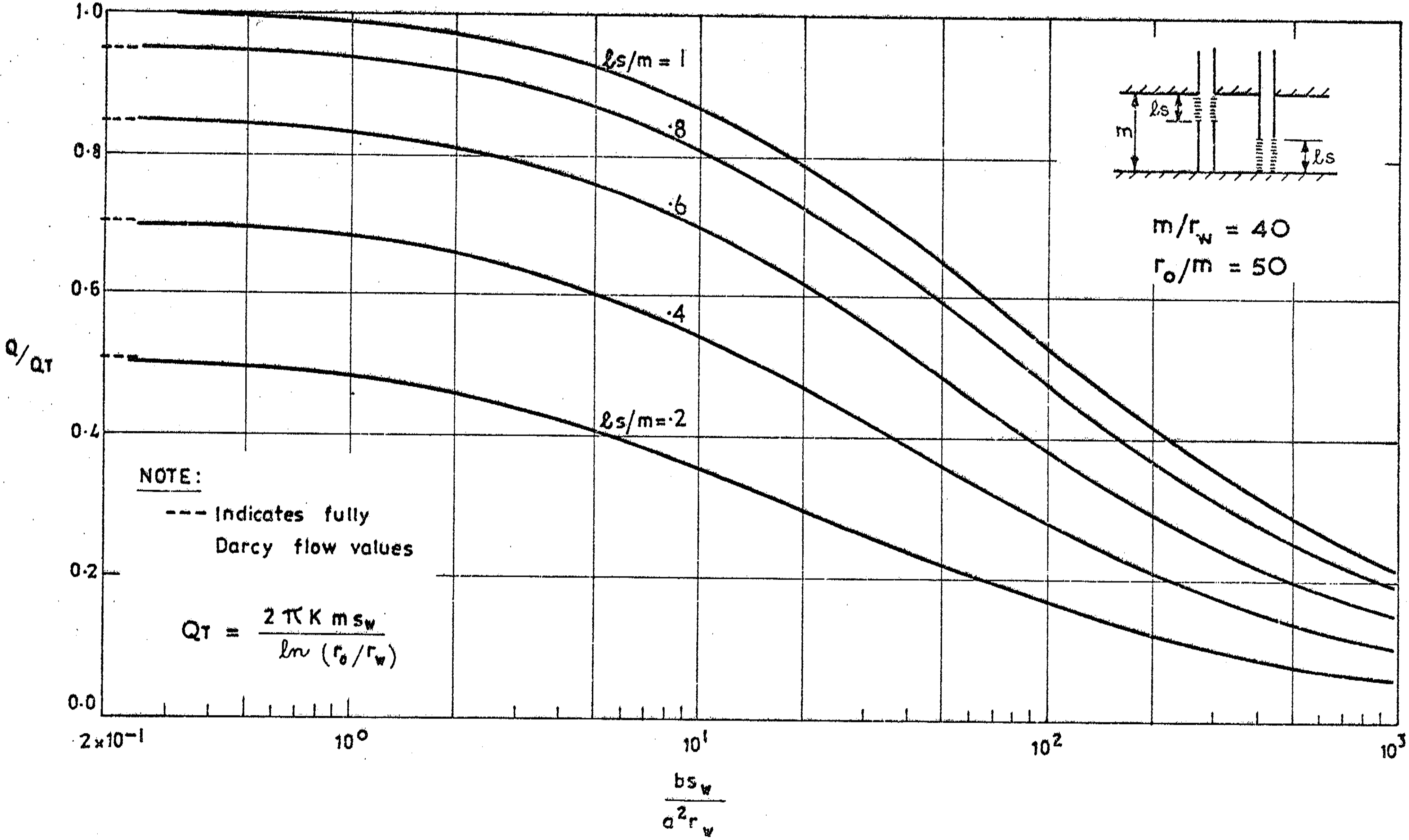


FIGURE 16: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

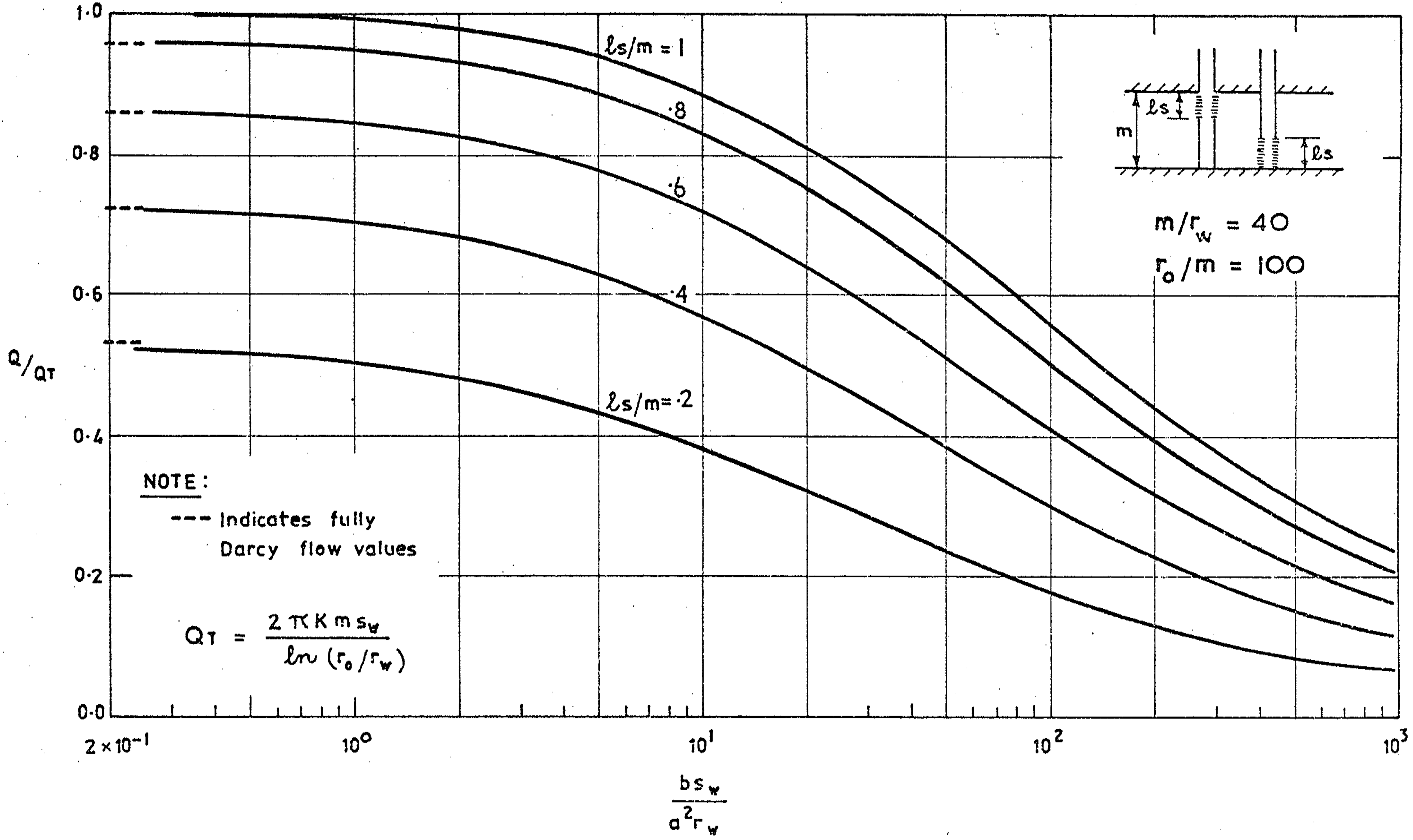
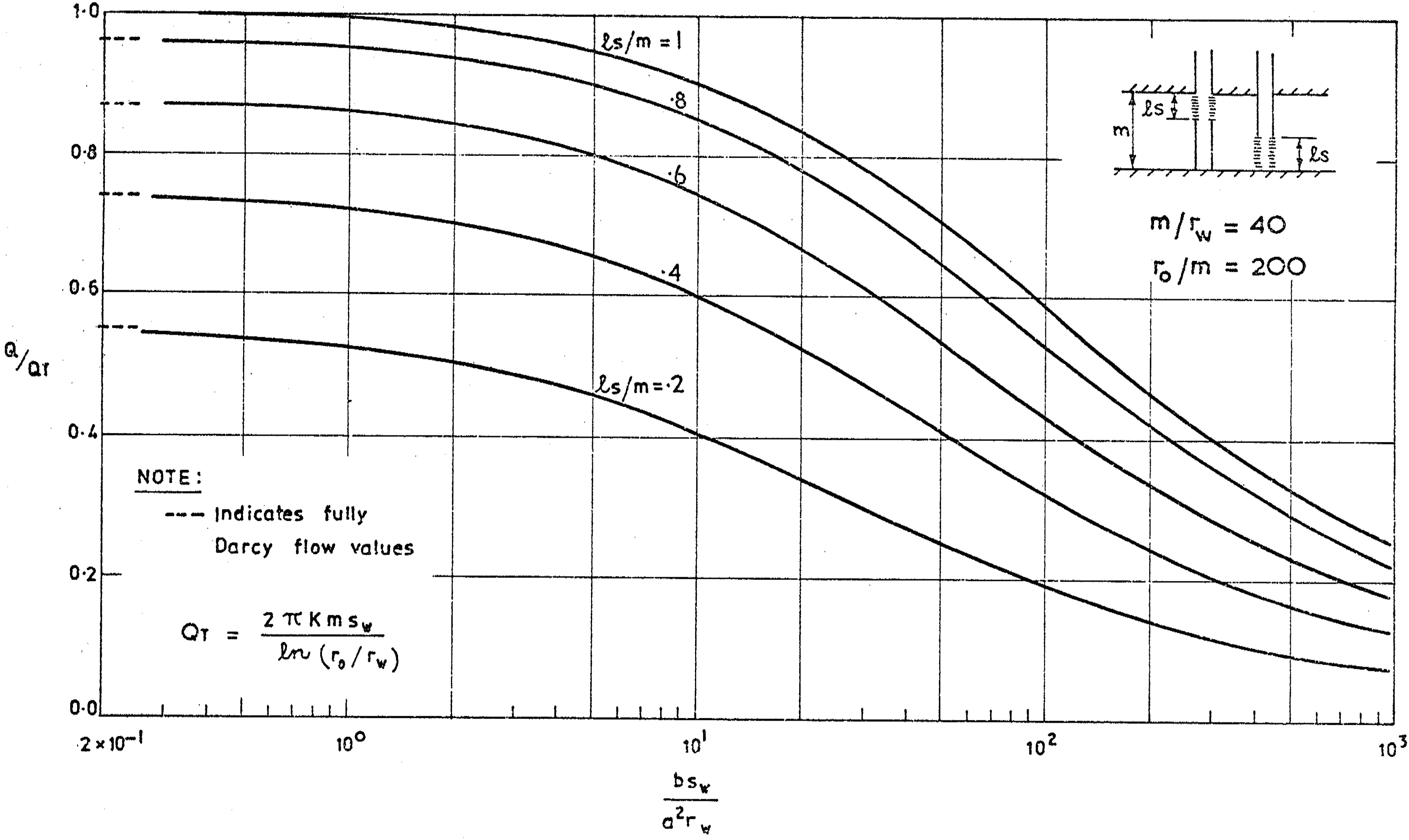


FIGURE 17: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER



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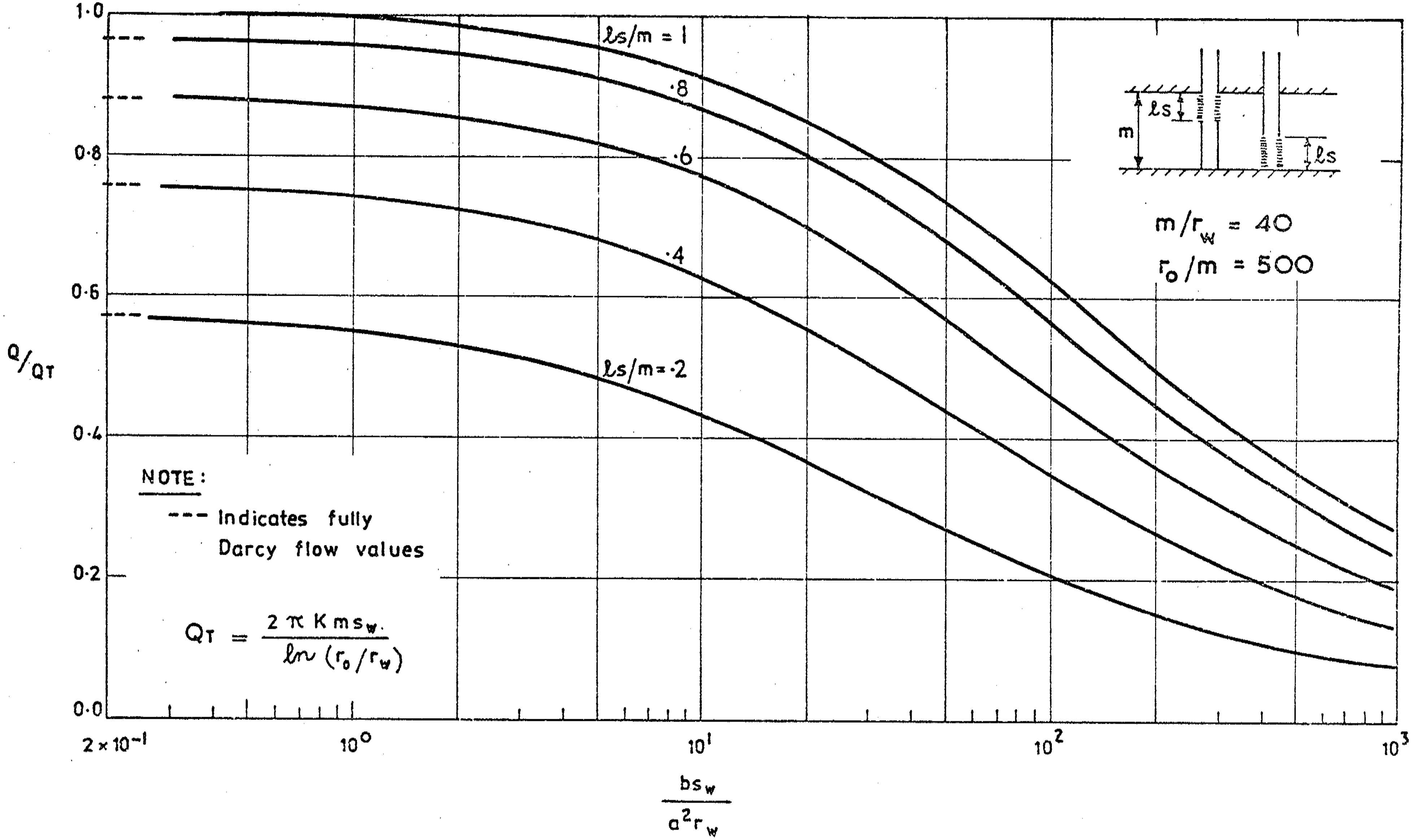

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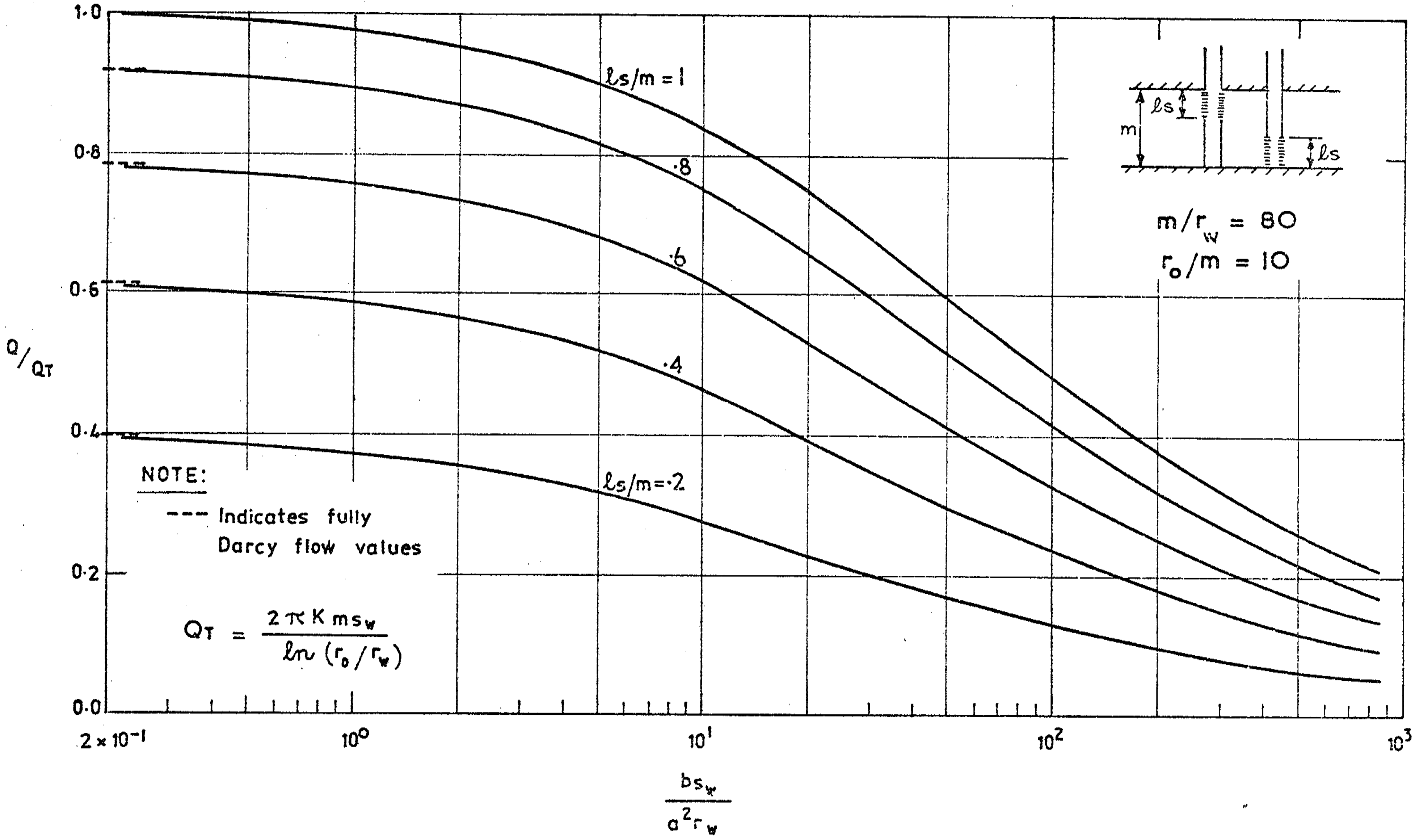

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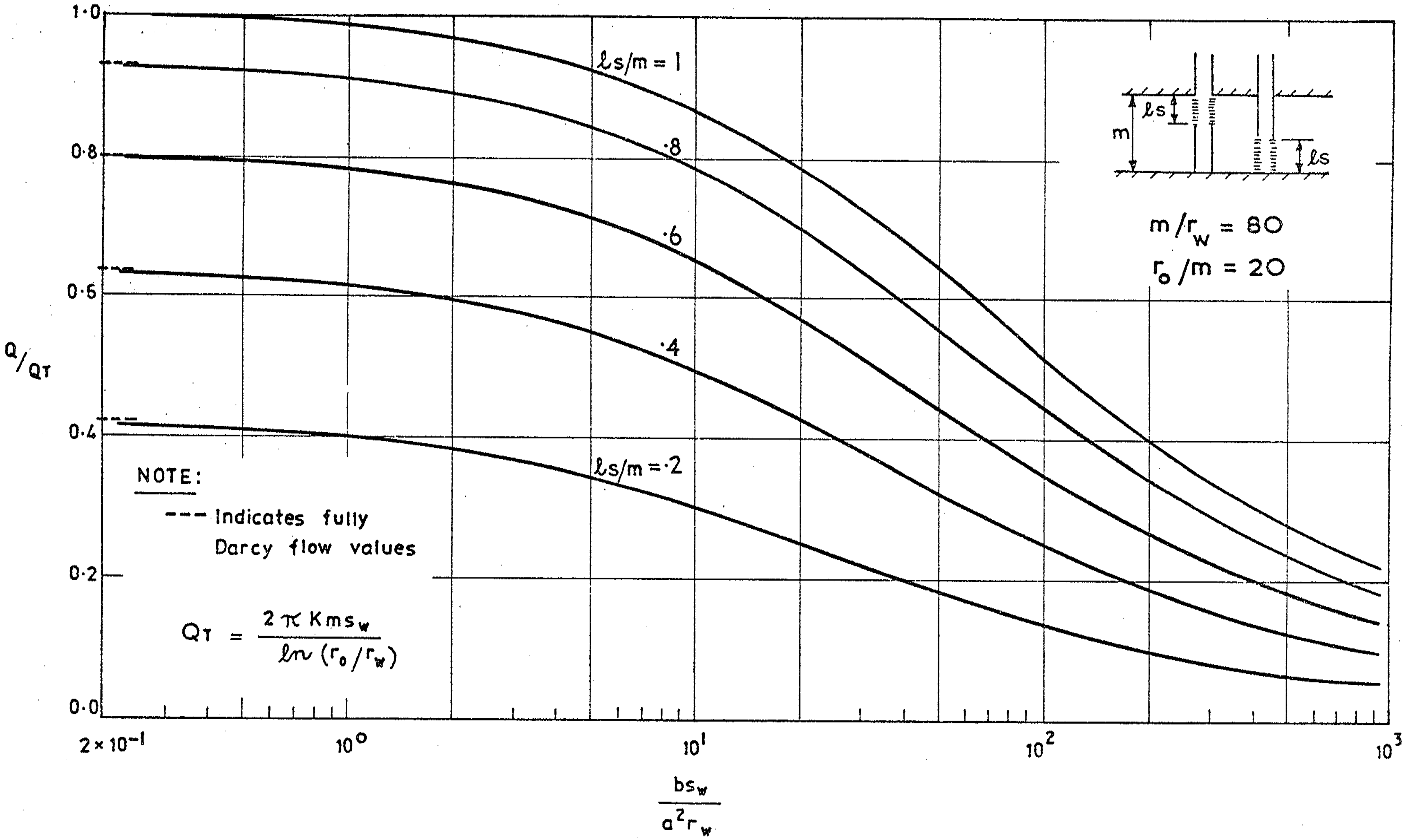


NOTE:

--- Indicates fully Darcy flow values

$$Q_T = \frac{2\pi K m s_w}{\ln(r_o/r_w)}$$

FIGURE 21: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

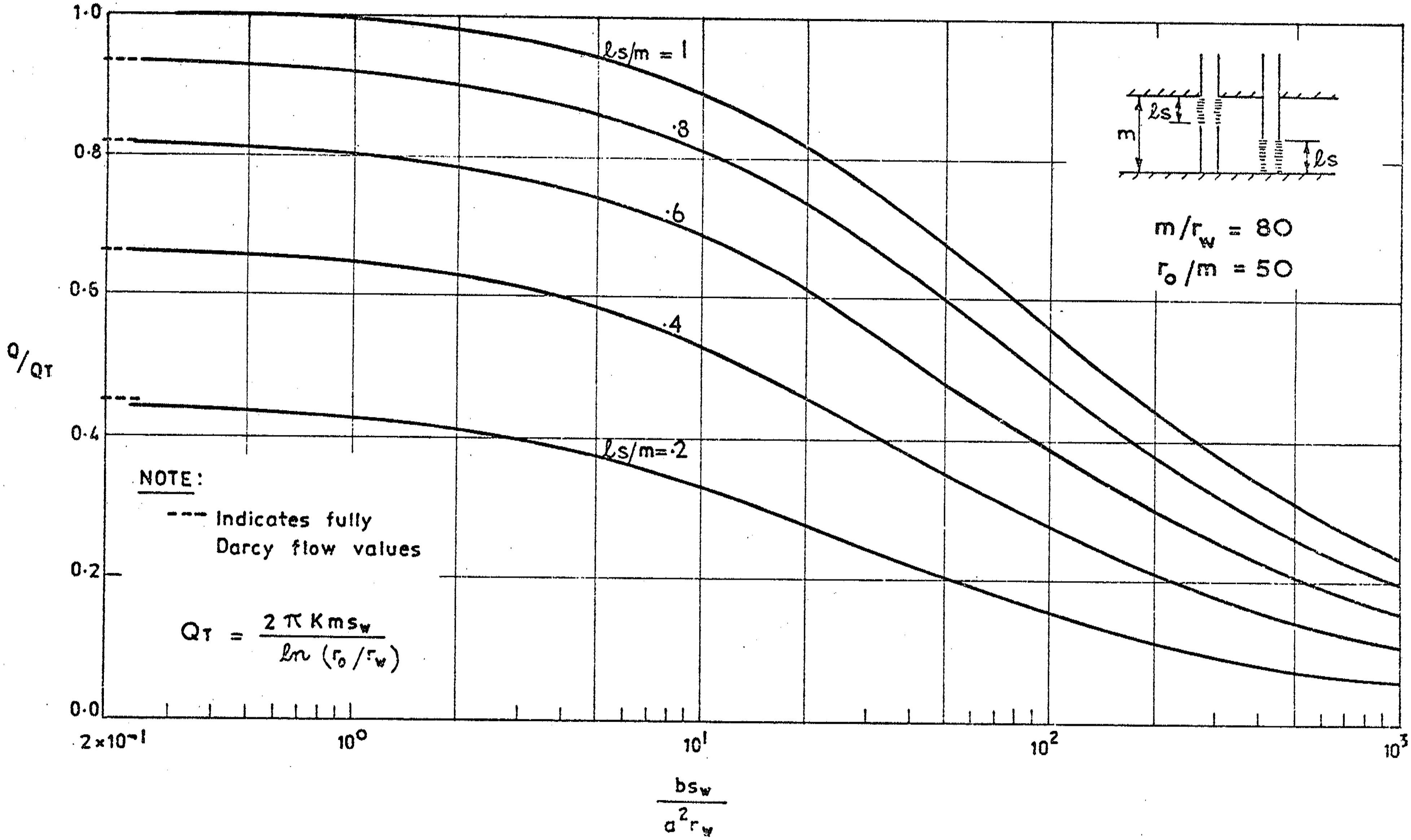
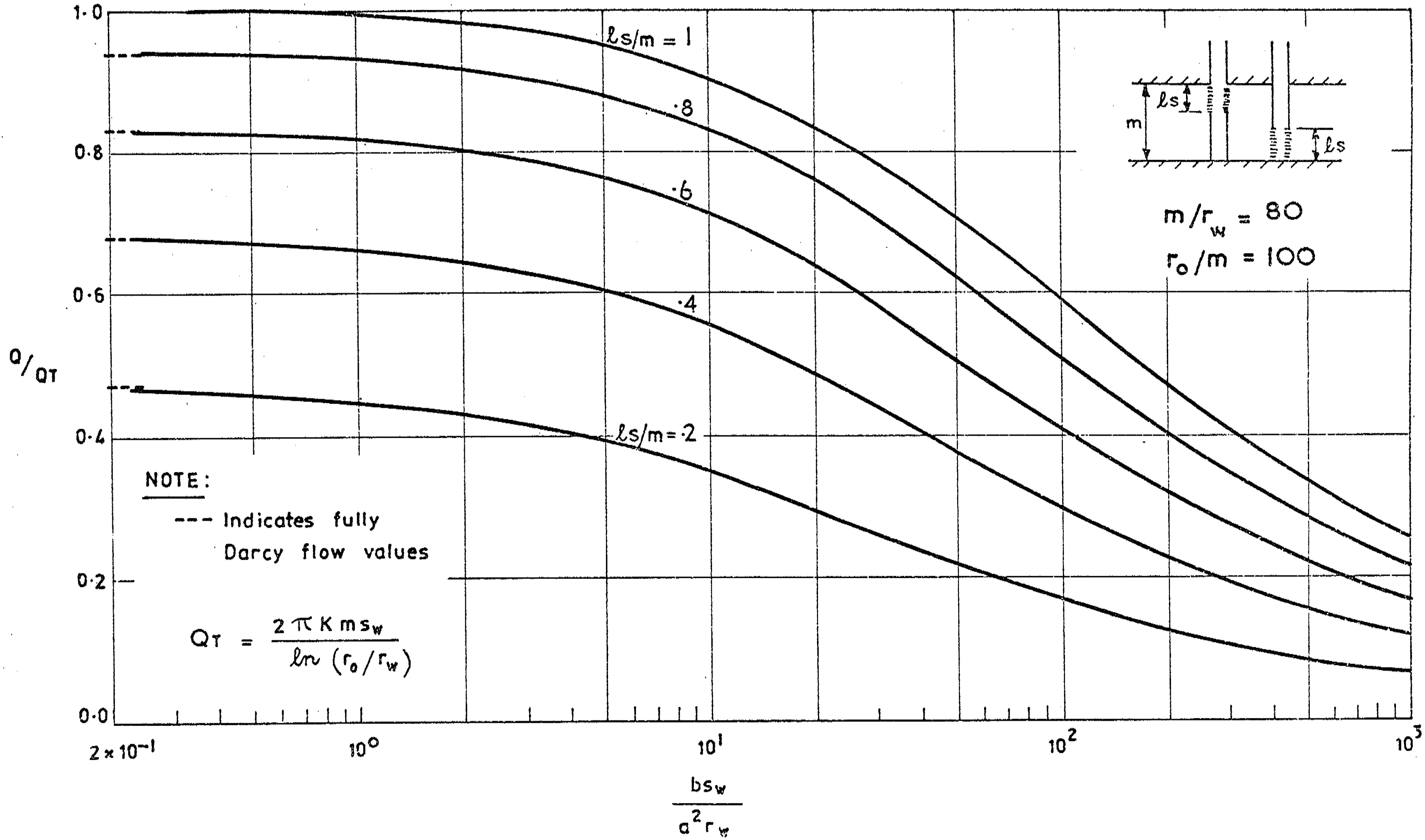


FIGURE 22: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER



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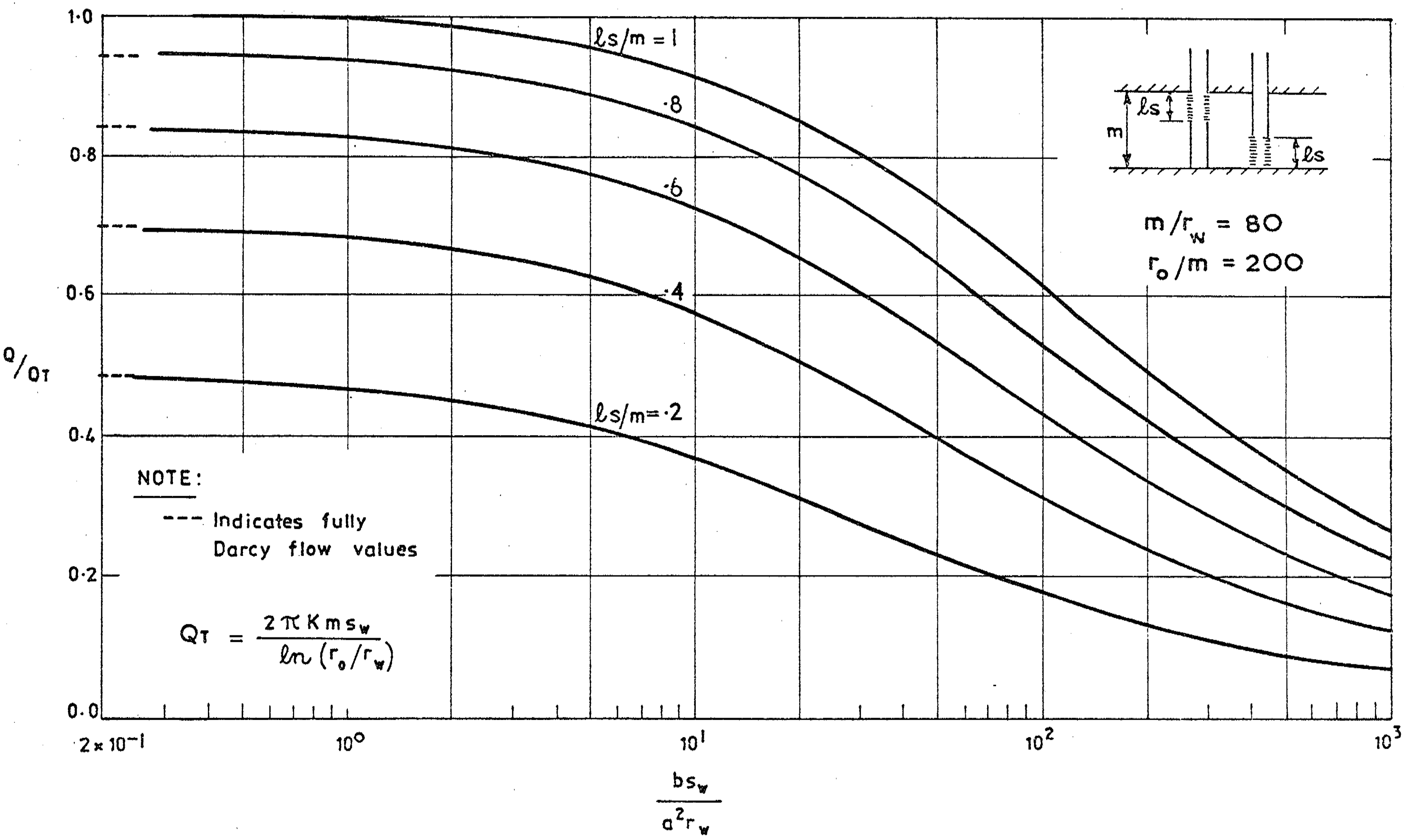


FIGURE 24: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

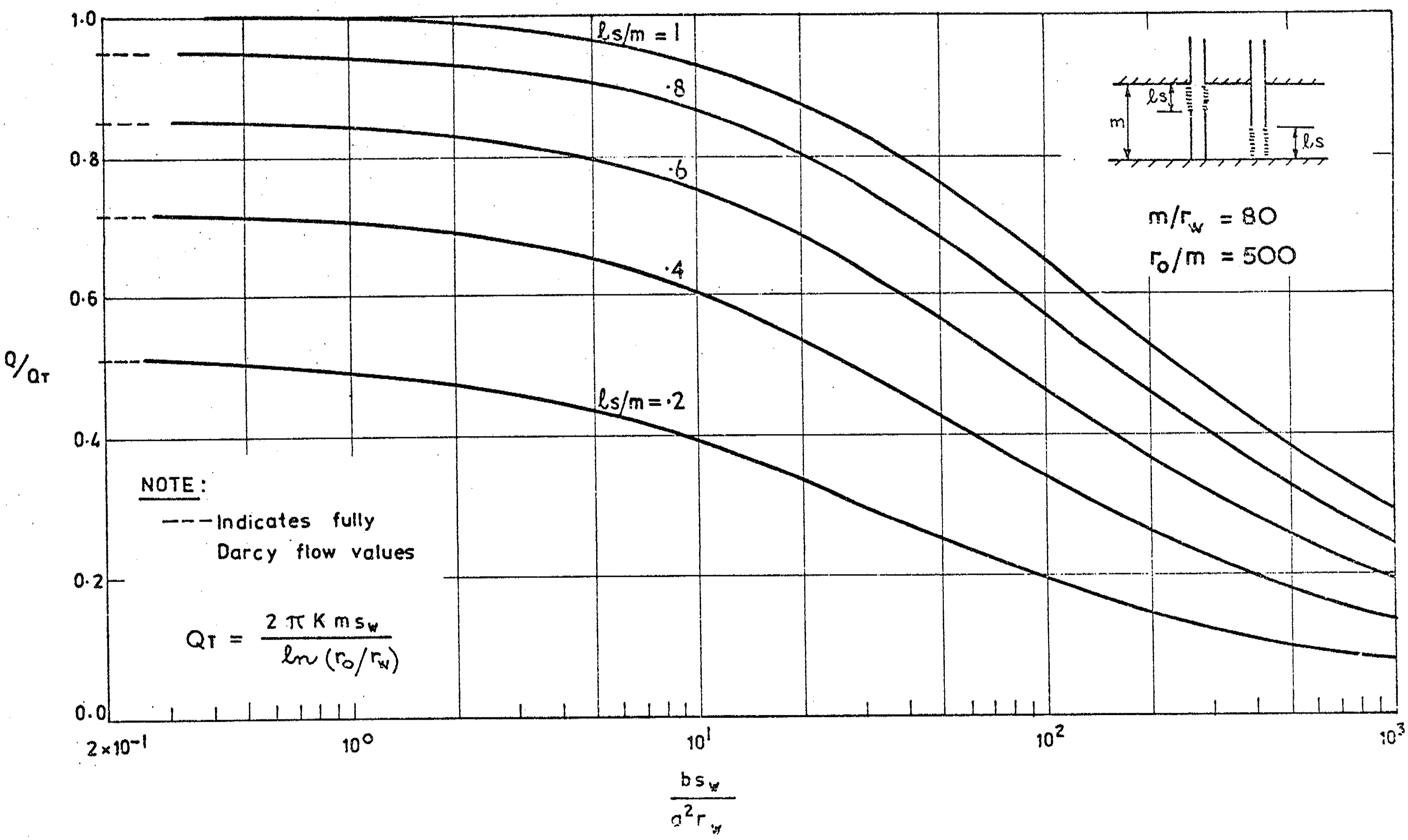


FIGURE 25: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP. CONFINED AQUIFER

may be used.

The simpler limiting cases of wholly Darcy flow and/or fully screened wells are incorporated in the more general non-Darcy partially screened design graphs. The non-Darcy flow graphs approach the Darcy flow counterparts as $\frac{b}{a^2} \rightarrow 0$. The non-Darcy graphs are based on the Forchheimer equation throughout the entire flow zone but, as has been pointed out above, only the high velocity flow near the well will be significantly non-linear.

(a) To Solve Particular Problems

The basic graphs, Figures 2 to 25, are best entered by selecting r_w and s_w values for given $\frac{r_o}{m}$, $\frac{l_s}{m}$ and $\frac{b}{a^2}$ ratios and predicting the discharge Q relative to the reference discharge Q_T. The discharges for various well geometries and given aquifer properties can then be compared for the same drawdown. For instance, the increase in discharge resulting from increasing the diameter of wells of otherwise constant geometry can be examined in this way. The following example shows the type of results which can be obtained.

Effect of Doubling Well Diameter

Example $m = 8$ metres, confined aquifer

$K = 10^{-1}$ cm.sec^{-1} $= 10^{-3}$ m.sec^{-1}

Choose $r_o = 1600$ metres

$\therefore \frac{r_o}{m} = 200$

(i) Wholly Darcy Flow

Percentage improvement is independent of drawdown s_w. Calculate for $s_w = 30$.

l_s/m	r_w				
	0.1 metre		0.2 metre		0.4 metre
	Q($l.s^{-1}$)	% increase in Q	Q($l.s^{-1}$)	% increase in Q	Q($l.s^{-1}$)
1	156	8	168	8	182
.6	131	11	146	10	161
.2	75	24	93	17	109

(ii) Non-Darcy Flow at Well

Assume $\frac{b}{a^2} = 0.5K^{1.25} = 2.8 \times 10^{-2}$

Calculate for s_w = 30 metres.

l_s/m	r_w				
	0.1 metre $Q(l.s^{-1})$	% difference in Q	0.2 metre $Q(l.s^{-1})$	% difference in Q	0.4 metre $Q(l.s^{-1})$
1	145	10	160	11	177
.6	115	19	137	13	155
.2	58	38	80	21	97

It can be seen that the basic data indicates that for small screening ratios and/or non-Darcy flow the improvement in discharge caused by doubling the well diameter can be significantly better than the 8% which occurs if the aquifer is fully screened and non-Darcy flow does not occur.

(b) To Plot Particular Drawdown-Discharge Curves

Sufficient data can be extracted from the dimensionless plots of Figures 2 to 25 to enable drawdown-discharge curves to be plotted for particular well geometries and aquifer characteristics. Each drawdown is taken in turn and the corresponding discharge calculated.

(c) To Prepare Graphs Displaying the Effect of Some Particular Variable

The data plotted in Figures 2 to 25 may be used to plot graphs showing the effect of a selected variable on well performance. For instance, the effect of the partial screening ratio may be isolated as shown in Figure 26 for wholly Darcy flow to a well for $\frac{r_o}{m} = 10$.

Similarly, the reduction in discharge caused by the occurrence of non-Darcy flow may be examined as illustrated in Figure 27 for fully screened wells.

4.2.3 Discharge Flux Distribution along Screens

Figure 28 shows typical discharge flux distributions for wholly Darcy flow into partially screened wells. The graph is drawn for $\frac{r_o}{m} = 10$ but the results apply for greater $\frac{r_o}{m}$ values.

Figure 29 shows typical discharge flux distributions when non-Darcy flow occurs near the well. It should be noted that in both cases the average discharge flux $\frac{Q}{l_s}$ and thus the average velocity occurs at a point 0.75 l_s along the screen from the end adjacent to a confining bed. The maximum discharge flux can exceed twice the average value for small

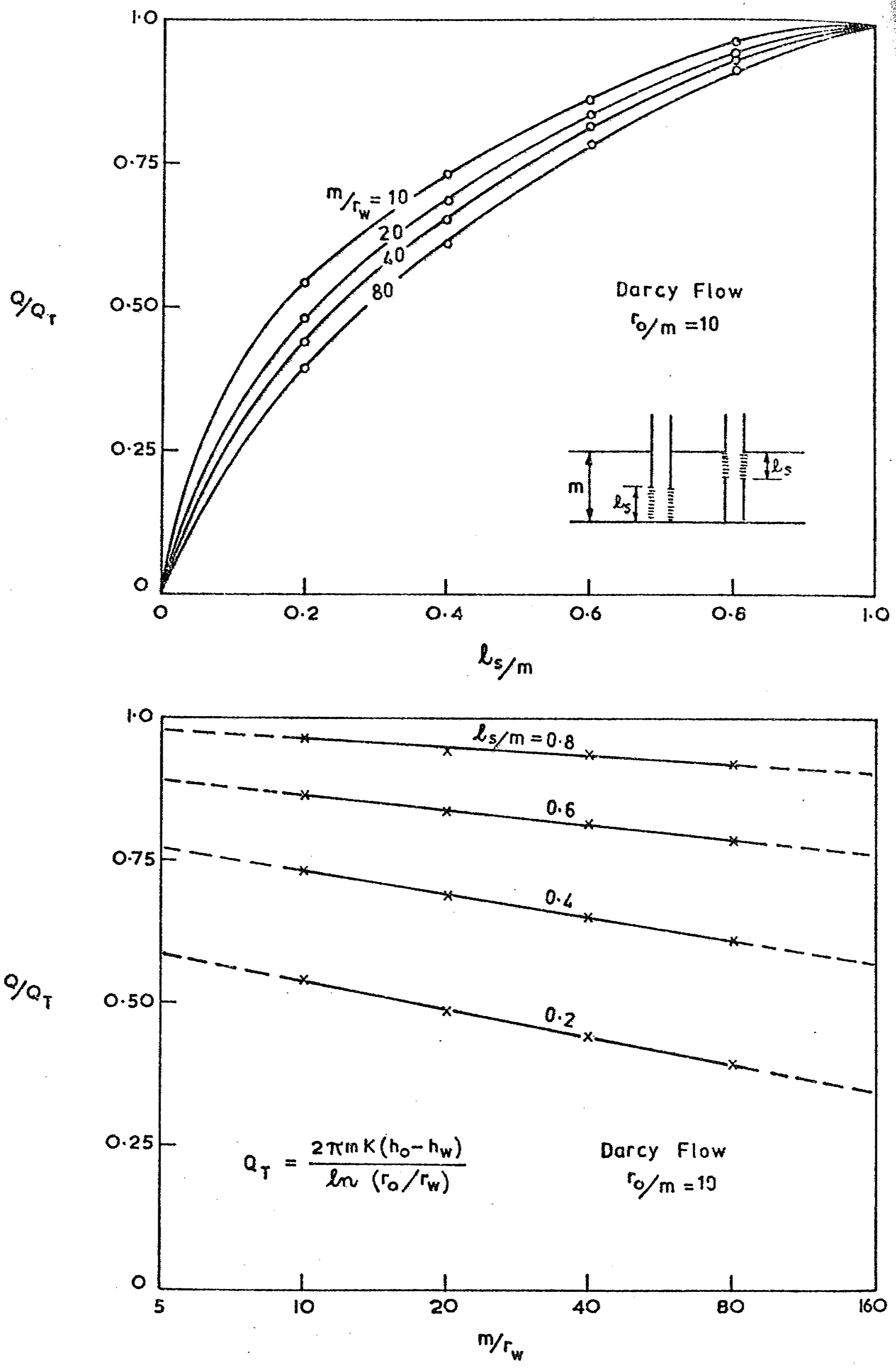


FIGURE 26: PARTIALLY SCREENED WELL IN A CONFINED AQUIFER. REDUCTION IN PERFORMANCE OF WELL FOR DARCY FLOW.

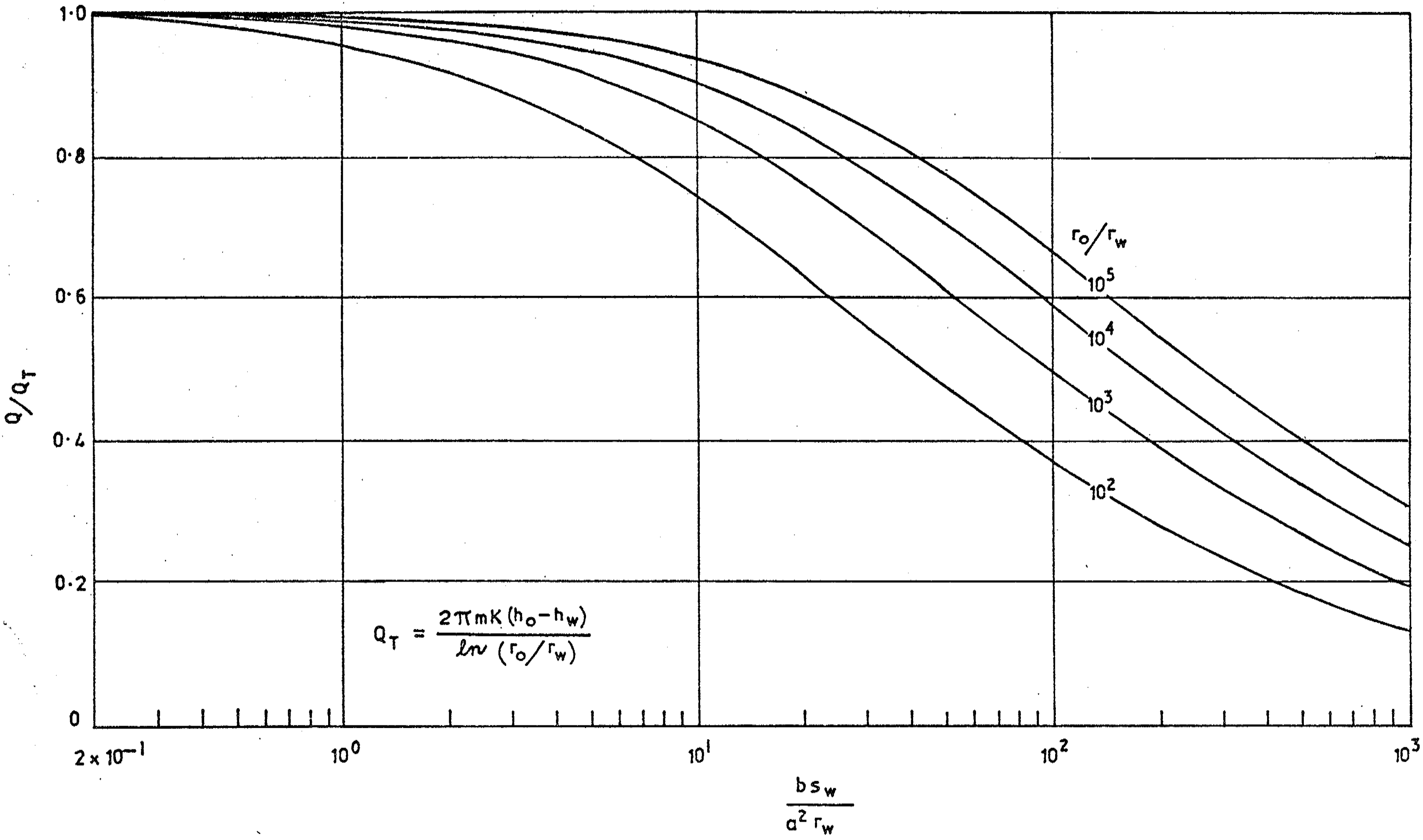


FIGURE 27: EFFECT OF NON-LINEAR FLOW ON WELL DRAWDOWN-DISCHARGE RELATIONSHIP FULLY SCREENED CONFINED AQUIFER

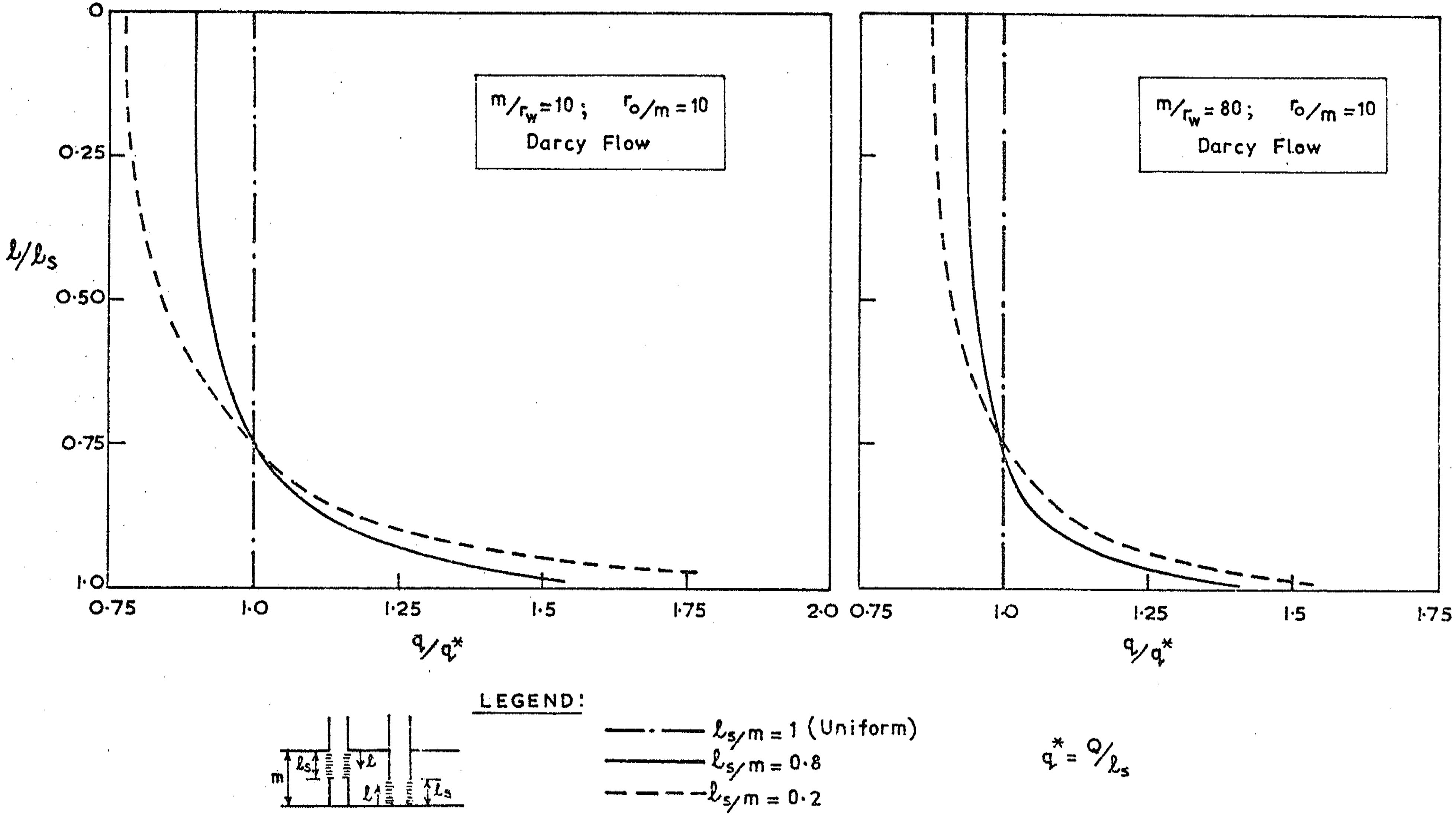
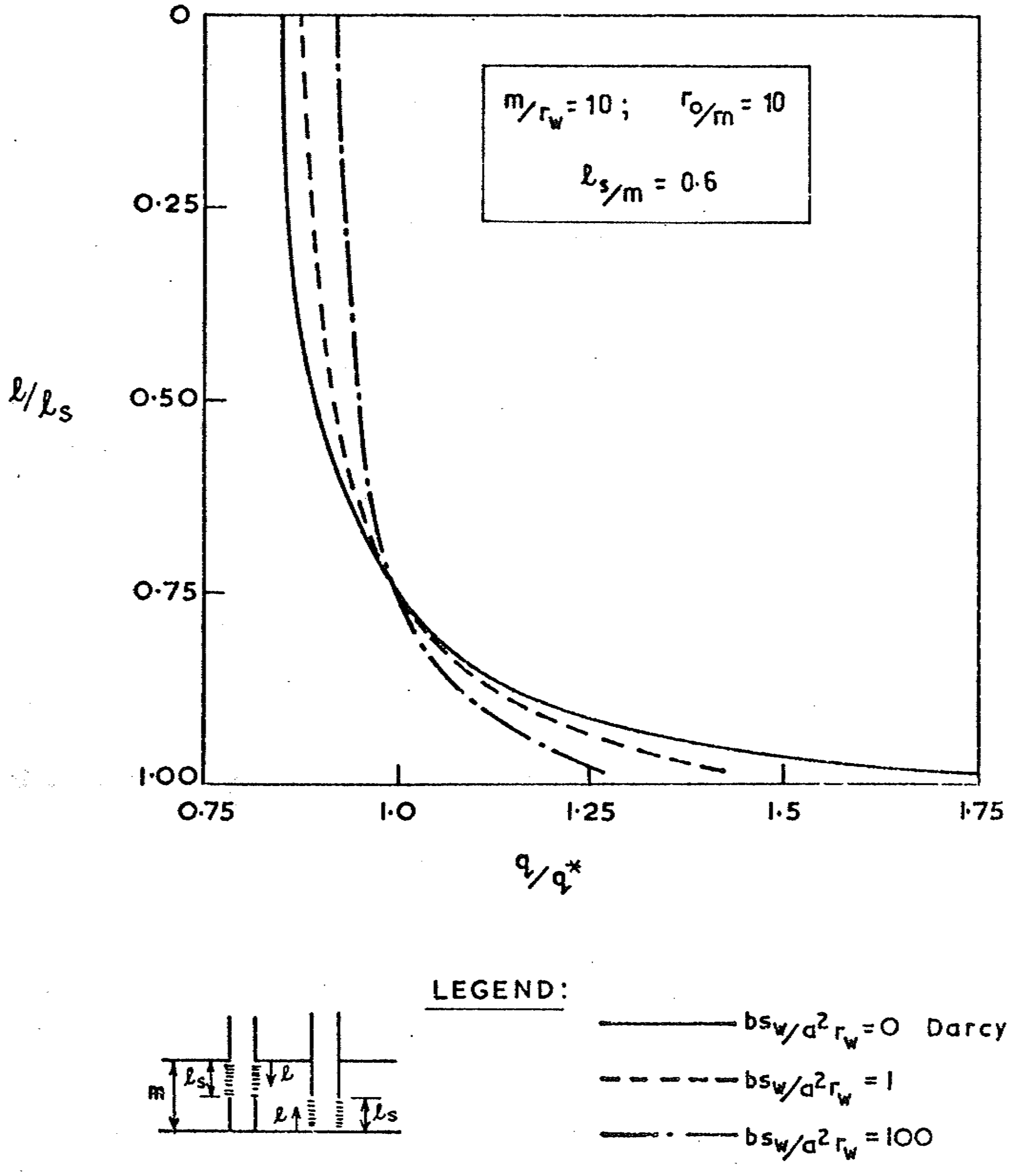


FIGURE 28: PARTIALLY SCREENED WELL IN A CONFINED AQUIFER TYPICAL DISCHARGE FLUX DISTRIBUTIONS ALONG SCREEN FOR DARCY FLOW



$q^* = Q/\ell_s$

FIGURE 29: PARTIALLY SCREENED WELL IN A CONFINED AQUIFER.
TYPICAL DISCHARGE FLUX DISTRIBUTIONS ALONG SCREEN FOR NON-LINEAR FLOW.

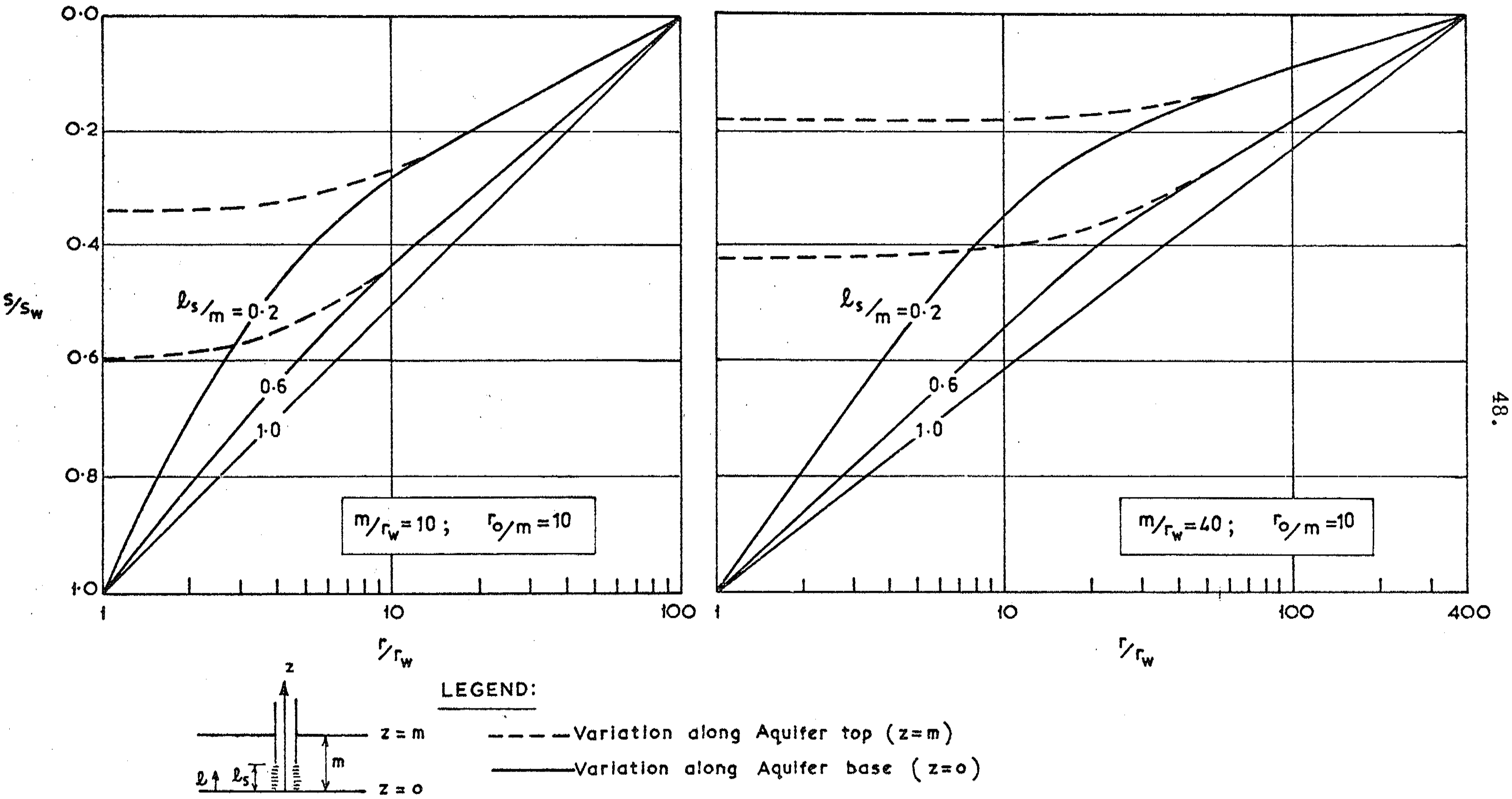


FIGURE 30: PARTIALLY SCREENED WELL IN A CONFINED AQUIFER
TYPICAL DRAWDOWN DISTRIBUTIONS ALONG AQUIFER BASE AND TOP FOR DARCY FLOW.

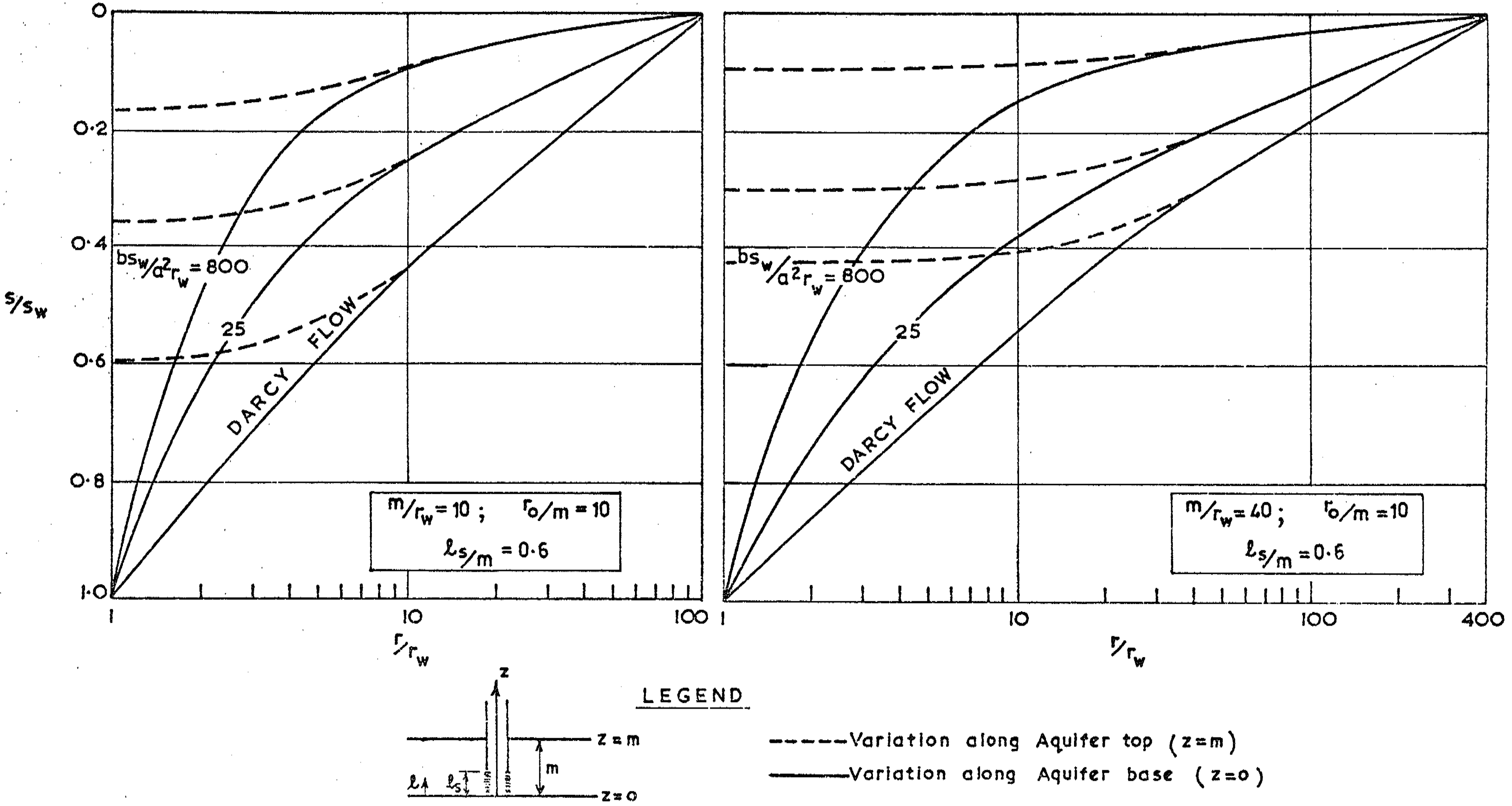
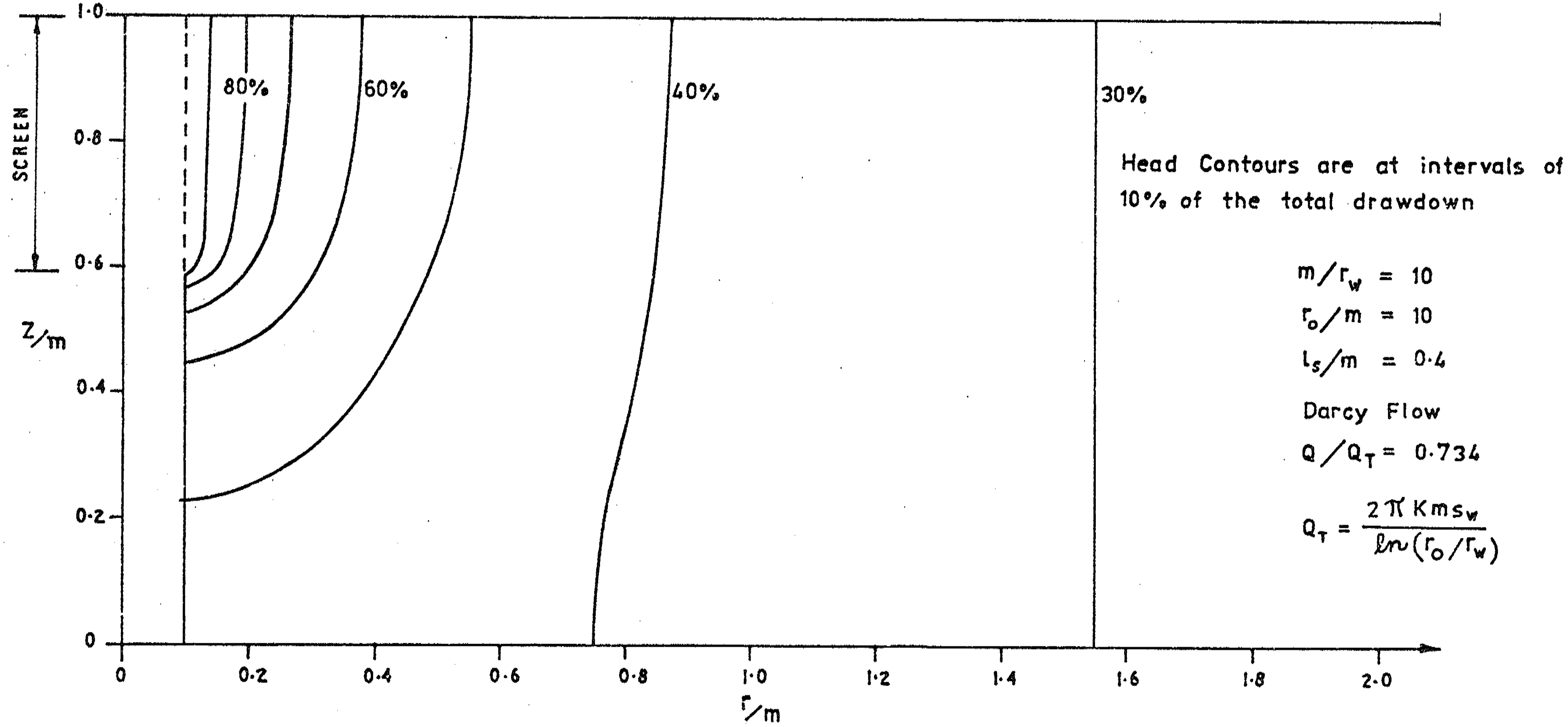


FIGURE 31: PARTIALLY SCREENED WELL IN A CONFINED AQUIFER TYPICAL DRAWDOWN DISTRIBUTIONS ALONG AQUIFER BASE AND TOP FOR NON-LINEAR FLOW



Head Contours are at intervals of 10% of the total drawdown

$m/r_w = 10$

$r_o/m = 10$

$l_s/m = 0{\cdot}4$

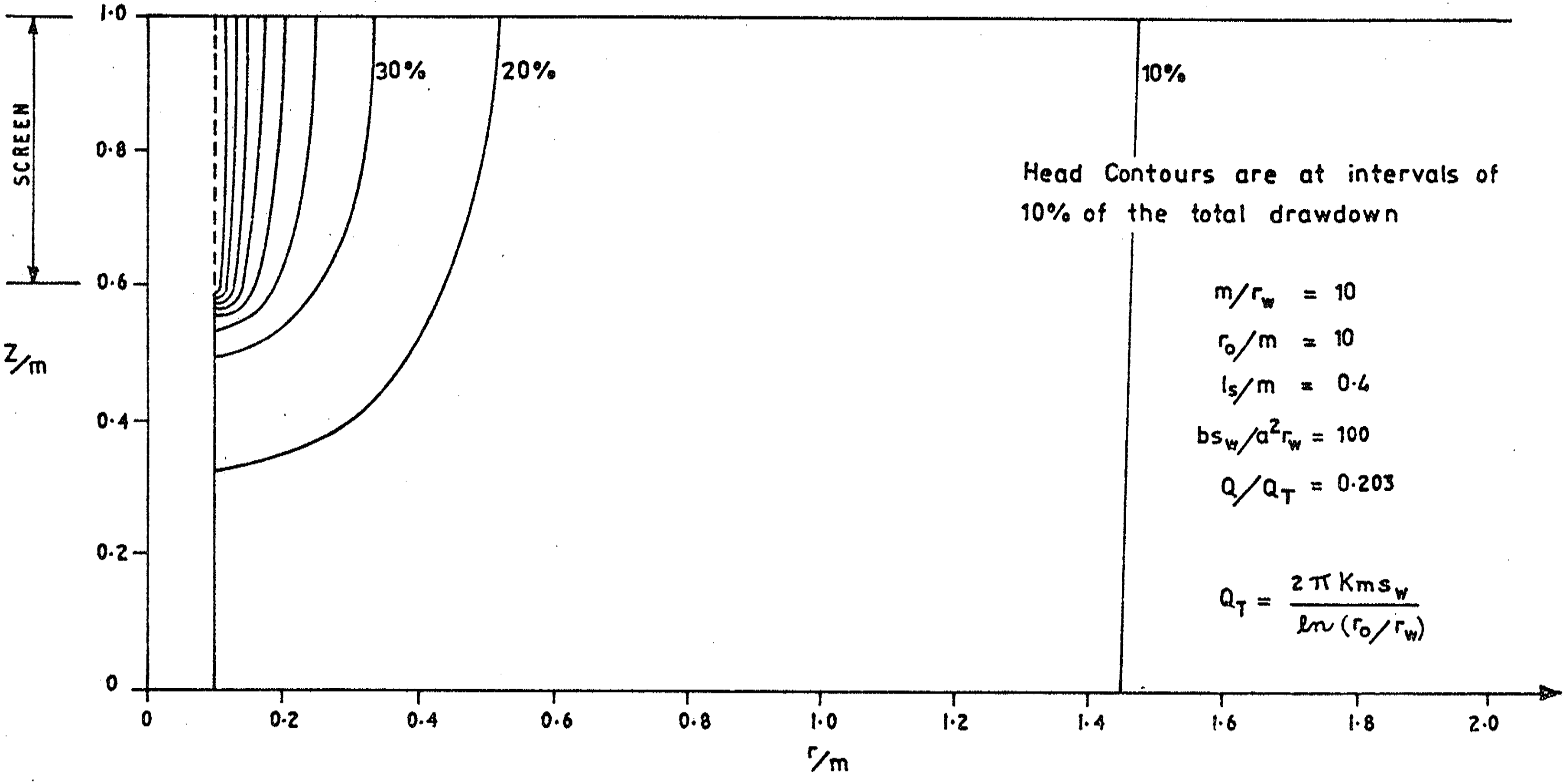
Darcy Flow

$Q/Q_T = 0{\cdot}734$

$$Q_T = \frac{2\pi K m s_w}{\ln(r_o/r_w)}$$

<u>FIGURE 32:</u> PARTIALLY SCREENED WELL IN A CONFINED AQUIFER.

TYPICAL HEAD DISTRIBUTION FOR DARCY FLOW



Head Contours are at intervals of 10% of the total drawdown

$m/r_w = 10$

$r_o/m = 10$

$l_s/m = 0{\cdot}4$

$bs_w/a^2r_w = 100$

$Q/Q_T = 0{\cdot}203$

$$Q_T = \frac{2\pi K m s_w}{\ln(r_o/r_w)}$$

FIGURE 33: PARTIALLY SCREENED WELL IN A CONFINED AQUIFER. TYPICAL HEAD DISTRIBUTION FOR NON-LINEAR FLOW.

values of the screening ratio l_s/m. The distribution becomes more uniform as complete screening is approached. When non-Darcy flow occurs, the greater the degree of non-linearity of the flow (as measured by $\frac{bs_w}{a^2 r_w}$) the more uniform the distribution becomes. The distribution will always be more uniform when non-Darcy flow occurs, all other things being equal.

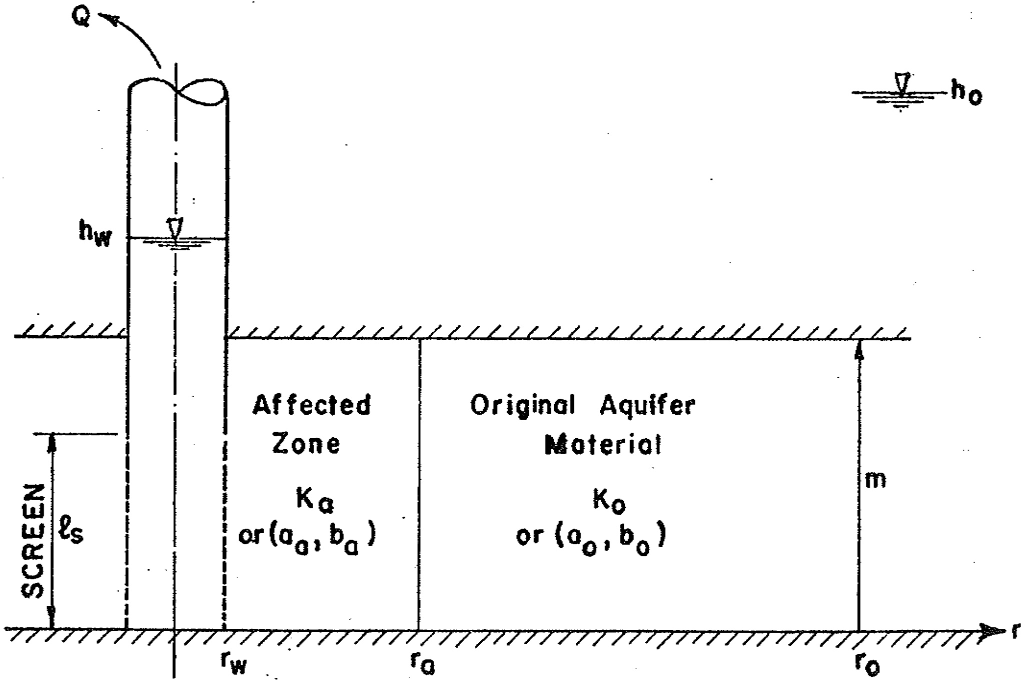
4.2.4 Drawdown and Head Distribution

Typical drawdown distributions for the top and base of the aquifer are given in Figures 30 and 31 for both wholly Darcy flow and non-Darcy flow. Although the graphs do not provide additional information on the well drawdown-discharge relationship they may be useful to designers in interpreting head measurements around constructed wells.

The distributionsof head throughout the aquifer near the well shown in Figures 32 and 33 are also provided as general information for designers. Amongst other uses, the location of screens in observation holes may be assisted by these plots.

4.3 Radial Inhomogeneity

The effect of a zone of altered permeability of radius r_a around a well in an otherwise homogeneous aquifer is shown in Figures 34 and 35. The sketch below defines the symbols used.



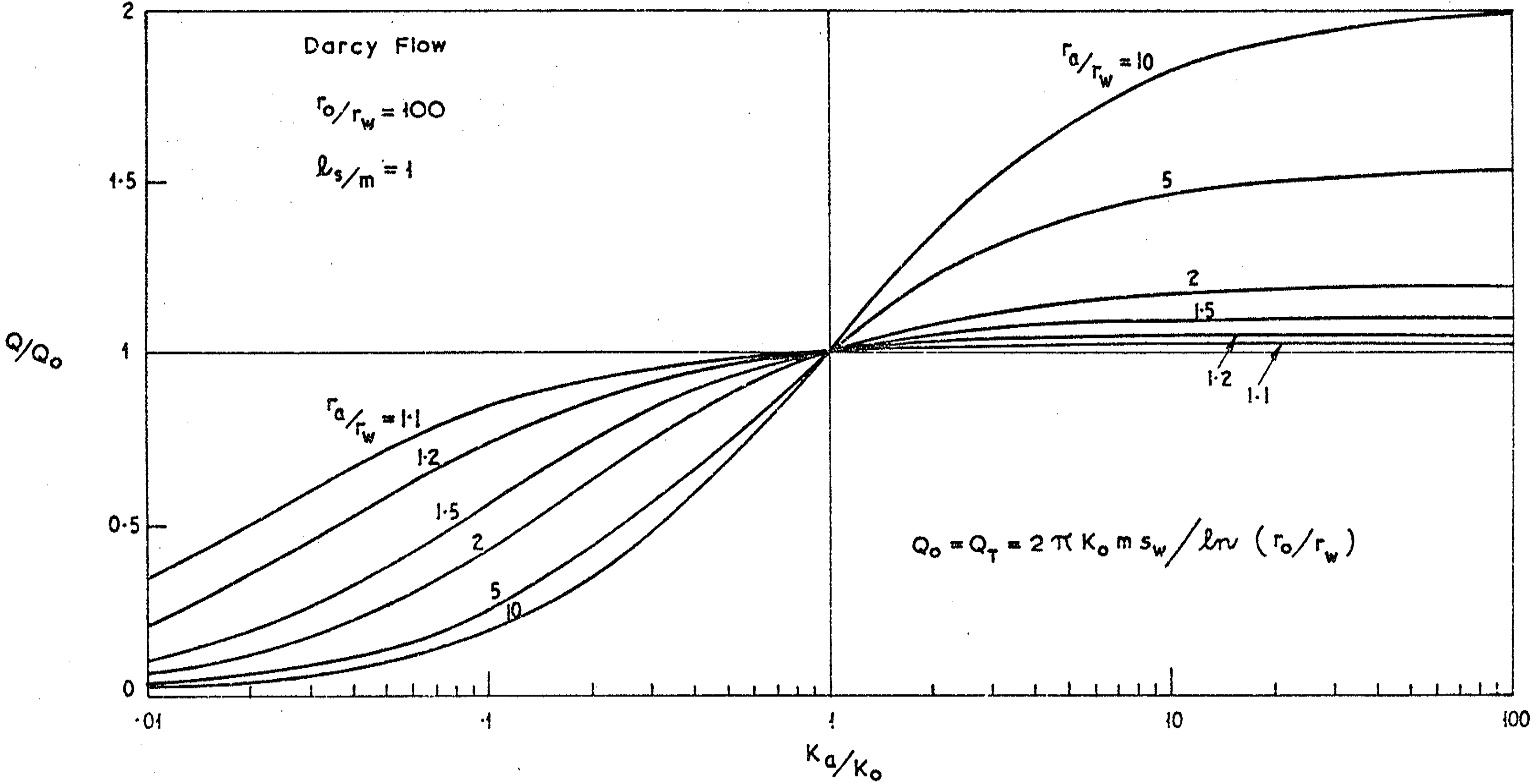
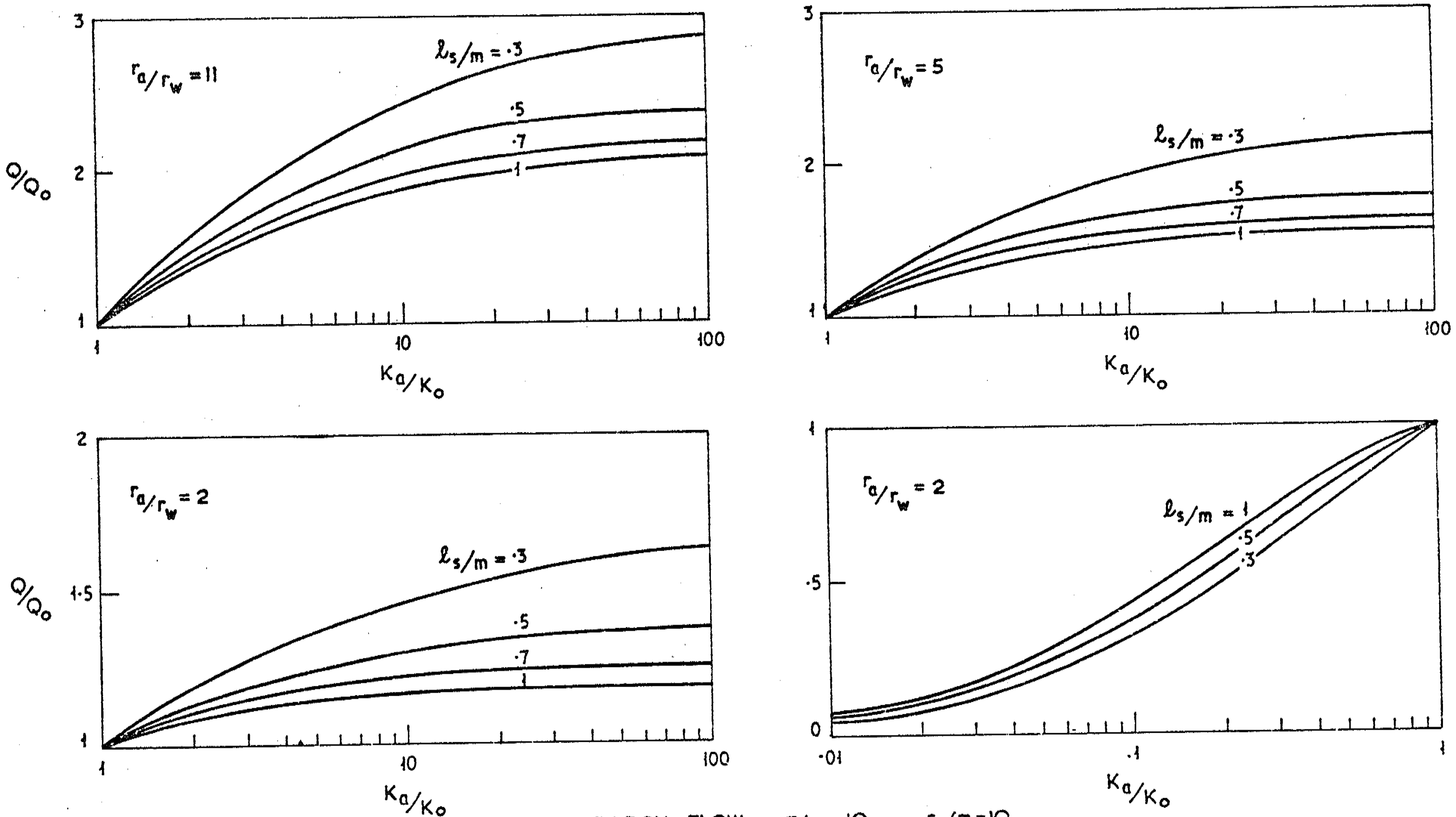


FIGURE 34: EFFECT OF RADIAL INHOMOGENEITY ON PERFORMANCE OF A FULLY SCREENED WELL IN A CONFINED AQUIFER



DARCY FLOW. $m/r_w = 10$. $r_o/m = 10$.

FIGURE 35: EFFECT OF RADIAL INHOMOGENEITY ON PERFORMANCE OF A PARTIALLY SCREENED WELL IN A CONFINED AQUIFER.

This inhomogeneity may be natural or may result from drilling or development. Values of $\frac{K_a}{K_o}$, the ratio of the permeability in the altered zone to the overall permeability, greater and less than unity indicate improved and reduced permeability respectively. The graph is for wholly Darcy flow.

The general case of non-Darcy flow to partially screened wells with radial inhomogeneity has not been treated. A very great number of graphs would have to be provided to cover such cases. However, analytical solutions can be obtained for the special case of non-Darcy flow to fully screened wells.

4.4 High Permeability "Fingers"

The improvement in performance of a well caused by the presence of "fingers" of material of higher permeability K_f and thickness m_f intersected by the well and extending to a radius r_f is illustrated by Table 1 and Figure 36. The example investigated is shown in the following sketch.

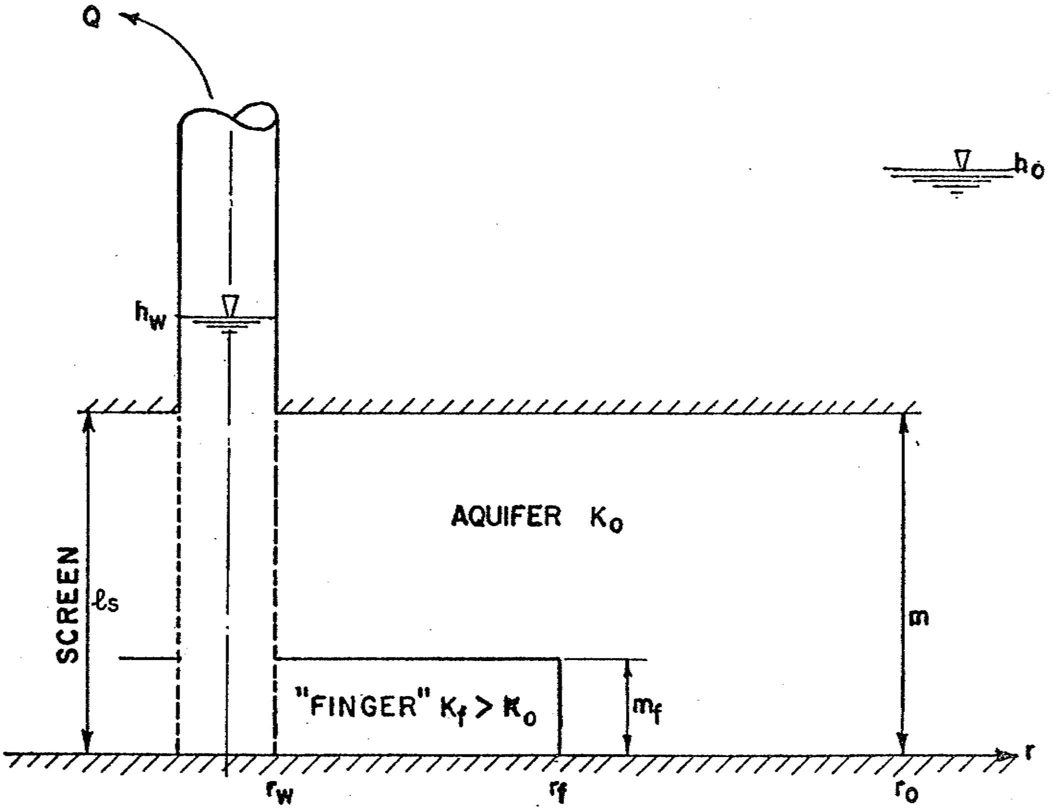
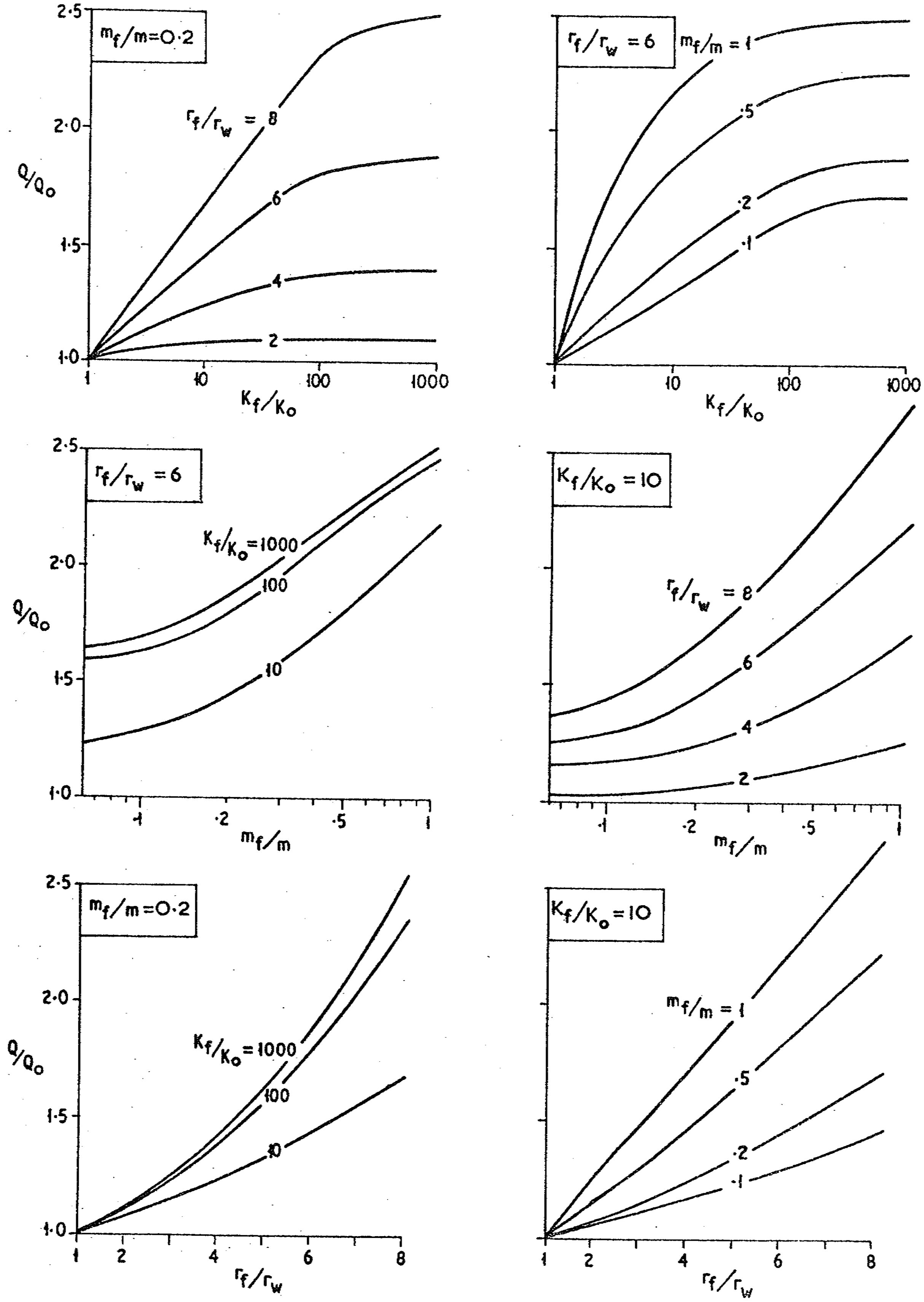


Table 1 : Improvement in Performance of a Fully Screened Well in a Confined Aquifer due to "Fingering" Effects. Tabulated Values of Q/Q_o Darcy Flow. $r_o/m = 2$.

m/r_w	K_f/K_o	r_f/r_w	m_f/m			
			1.0	0.5	0.2	0.1
20	10	2	1.20	1.14	1.07	1.06
		4	1.51	1.35	1.19	1.14
		6	1.78	1.55	1.31	1.22
		8	2.03	1.75	1.42	1.29
		r_o/r_w	10	5.5	2.8	1.9
	100	2	1.23	1.15	1.08	1.06
		4	1.59	1.43	1.25	1.19
		6	1.93	1.72	1.45	1.35
		8	2.26	2.02	1.67	1.54
		r_o/r_w	100	50.5	20.8	10.9
	1000	2	1.23	1.16	1.08	1.07
		4	1.60	1.44	1.26	1.20
		6	1.94	1.74	1.47	1.38
		8	2.29	2.06	1.71	1.59
		r_o/r_w	1000	500.5	200.8	100.9
10	10	2	1.26	1.16	1.08	1.06
		4	1.71	1.45	1.24	1.18
		6	2.17	1.84	1.45	1.30
		8	2.67	2.20	1.68	1.45
		r_o/r_w	10	5.5	2.8	1.9
	100	2	1.30	1.19	1.10	1.07
		4	1.85	1.62	1.38	1.28
		6	2.45	2.20	1.81	1.65
		8	3.20	2.85	2.32	2.00
		r_o/r_w	100	50.5	20.8	10.9
	1000	2	1.30	1.20	1.10	1.08
		4	1.86	1.67	1.40	1.30
		6	2.49	2.25	1.88	1.72
		8	3.26	2.91	2.50	2.20
		r_o/r_w	1000	500.5	200.8	100.9
5	10	2	1.37	1.25	1.13	1.07
		4	2.18	1.83	1.45	1.30
		6	3.34	2.55	1.75	1.45
		8	5.34	3.60	2.20	1.67
		r_o/r_w	10	5.5	2.8	1.9
	100	2	1.43	1.32	1.19	1.11
		4	2.48	2.19	1.81	1.60
		6	4.36	3.72	2.68	2.35
		8	9.44	7.20	5.10	4.00
		r_o/r_w	100	50.5	20.8	10.9
	1000	2	1.43	1.33	1.20	1.12
		4	2.51	2.20	1.88	1.75
		6	4.49	3.85	2.93	2.60
		8	10.22	8.00	6.20	5.30
		r_o/r_w	1000	500.5	200.8	100.9



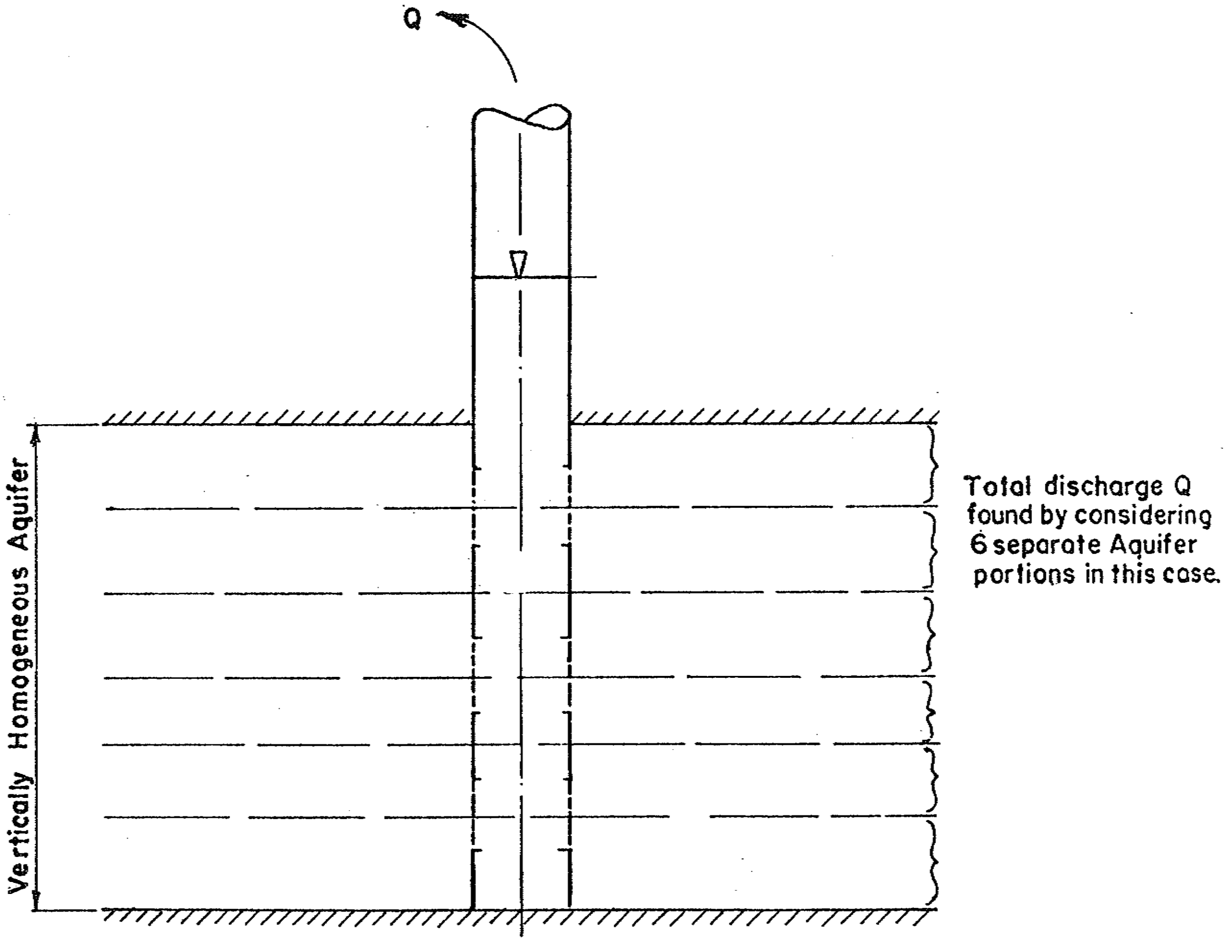
DARCY FLOW. FULLY SCREENED. $m/r_w = 10$, $r_o/m = 2$, $Q_o = 2\pi K_o m s_w / \ln (r_o/r_w)$

FIGURE 36: TYPICAL EFFECTS OF A HIGH PERMEABILITY "FINGER" ON THE PERFORMANCE OF A WELL IN A CONFINED AQUIFER.

Only wholly Darcy flow is considered. More complex cases involving non-Darcy flow need individual numerical solution. The computation cost for such cases would be relatively high because of the fine mesh required in the finite element analysis.

4.5 Vertically Homogeneous Aquifer, Multiple Screens

If multiple screened lengths are used in vertically homogeneous confined aquifers the total discharge for a given drawdown in the well can be predicted by subdividing the aquifer by horizontal planes drawn through mid-points of screens and midway between adjacent screens as shown in the sketch below.



Each portion of the aquifer can then be treated as a separate aquifer using the information provided in previous sections. Superposition will give the total well discharge.

The technique described has been used to examine the effect of placing a partial screen at the mid-point of the aquifer rather than at the top or bottom. The method was checked by comparing results with finite element solutions obtained by direct use of the computer programs for several cases.

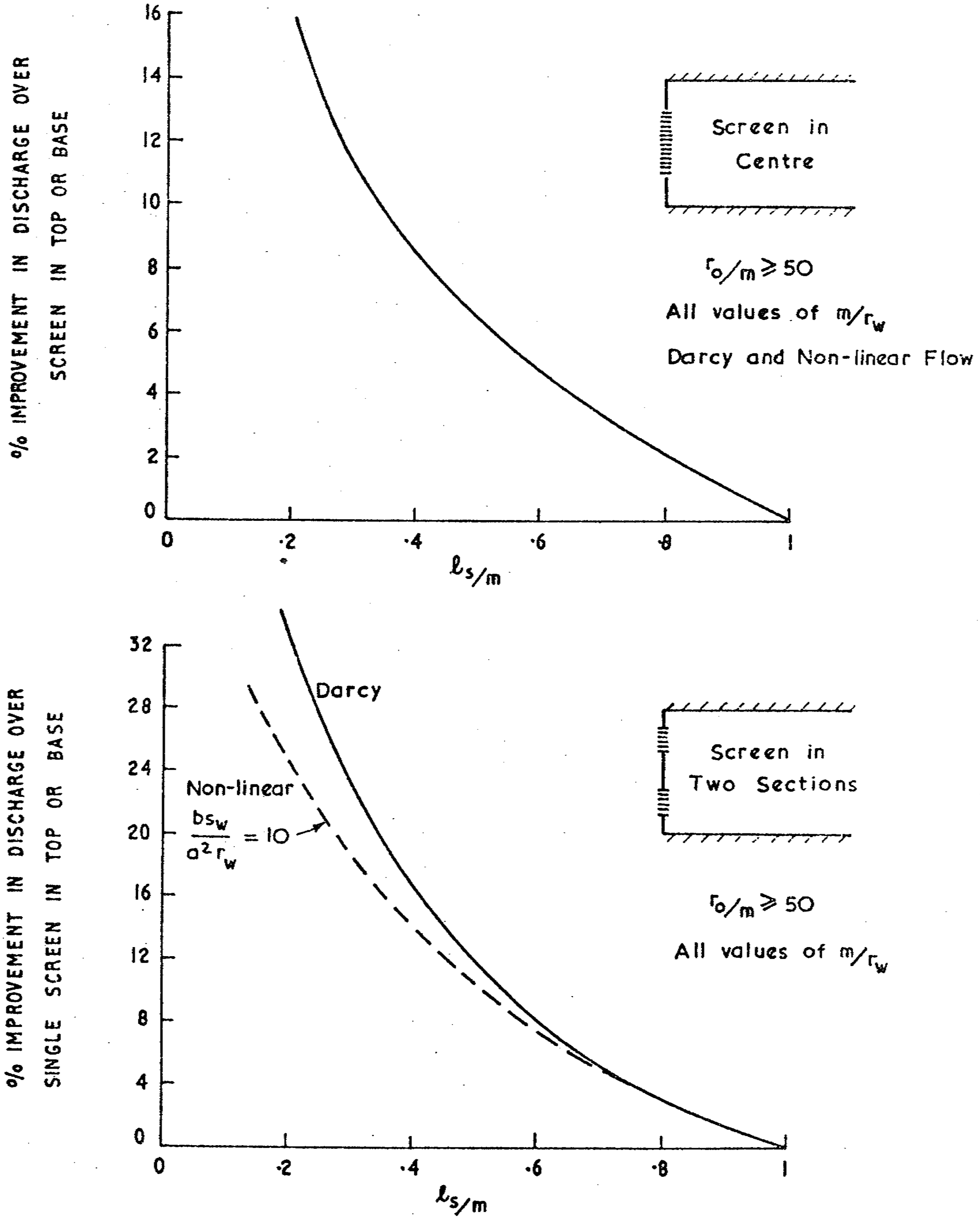


FIGURE 37: IMPROVEMENT IN WELL PERFORMANCE ARISING FROM MULTIPLE SCREENING OF A CONFINED AQUIFER.

Results were found to be identical. Similarly, the effect of dividing a screen into two portions was investigated. The results for both of these screen configurations are presented in Figure 37. For $\frac{r_o}{m} > 50$, the condition usually met in practice, the improvement over a single screen at the top or bottom of the aquifer was found to be independent of $\frac{m}{r_w}$. The high percentage improvement in discharge shown on the figure for small values of the screening ratio $\frac{l_s}{m}$ should encourage the designer to consider multiple screening.

4.6 Multilayered Aquifers

4.6.1 Fully Screened Well, Wholly Darcy Flow

The total well discharge for a given drawdown can be calculated by adding the discharge from each layer treated as a separate aquifer.

4.6.2 Fully Screened Well, Non-Darcy Flow in One or More Layers

Complex cases may be solved by direct application of the computer programs.

For a two layered aquifer in which non-Darcy flow occurs in one layer it has been found that the error in well discharge caused by adding discharges from individual layers determined using Figures 2 to 25 is not significant for the following conditions (Cox (1976))

$$10 \leqslant \frac{m}{r_w} \leqslant 100$$

$$\frac{r_o}{m} \geqslant 10$$

$$.2 \leqslant \frac{m_2}{m} \leqslant .8$$

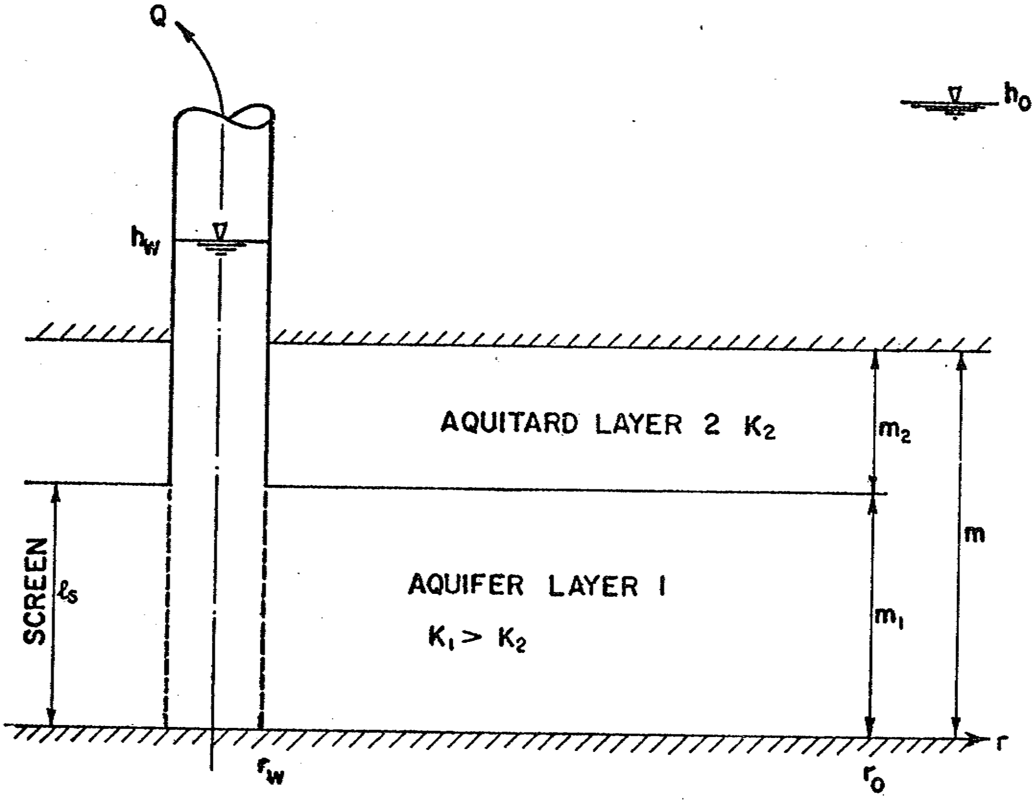
$$\frac{b s_w}{a^2 r_w} \leqslant 25$$

where m_2 is the thickness of the layer in which non-Darcy flow occurs and m is the total aquifer thickness.

4.6.3 Partially Screened Wells

Particular cases must be solved by direct use of the computer programs as the number of variables is too great to allow all cases to be covered by a reasonable number of dimensionless plots.

For the special case of wholly Darcy flow in a two-layer aquifer in which the more permeable layer (aquifer) is fully screened and the other layer (aquitard) is unscreened the effect of the unscreened layer on the flow can be ignored if $\frac{m_1K_1}{mK_2} > 10$. The symbols are defined in the following sketch.



5. Wells in Unconfined Aquifers

5.1 Non-dimensional Groupings of Variables

The dimensionless groups in terms of which well performance tables and graphs have been prepared are:-

$$\frac{Q}{Kh_o^2}\ (= \frac{aQ}{h_o^2}),\quad \frac{r_o}{h_o},\quad \frac{h_o}{r_w},\quad \frac{l_s}{h_o},\quad \frac{h_w}{h_o},\quad \frac{b}{a^2}$$

The variables have been defined previously in Figure 1(b).

Again the user of the tables and graphs is reminded that if non-Darcy flow occurs it will do so only in a limited zone near the well. Outside this zone the non-linear term in the Forchheimer equation becomes insignificant. As for wells in confined aquifers, the general non-Darcy flow graphs approach the simpler wholly Darcy flow condition as $\frac{b}{a^2} \rightarrow 0$.

5.2 Well Screened at Base of Homogeneous Unconfined Aquifer

5.2.1 Wholly Darcy Flow, Well Drawn Down to Top of Screen

Table 2 gives data which allows the discharge and free surface water level just outside the well to be calculated if the water level in the well is drawn down to level with the top of the screen, there is no head loss through the screen and the flow is wholly Darcy. A typical plot showing part of this data for $\frac{r_o}{h_o} = 2$ is provided in Figure 38. It can be seen from the figure that the Dupuit equation ($Q = \pi K(h_o^2 - h_w^2)/\ln(\frac{r_o}{r_w})$) gives satisfactory accuracy if 70% or more of the aquifer is screened.

It should also be noted that for wells drawn down to the top of a screen placed at the base of the aquifer the maximum discharge and free surface drawdown occur when between 40% and 50% of the aquifer is screened. Maximum values are shown in Figure 39 for a range of $\frac{h_o}{r_w}$ and $\frac{r_o}{h_o}$ values. These are maximum possible values for discharges from wells in unconfined aquifers without screen de-watering.

Typical drawdown distributions are shown in Figure 40.

A typical distribution of head within the aquifer is shown in Figure 41.

Typical discharge flux distributions along the screen are shown in Figure 42. It can be seen that for wells in unconfined aquifers, as in confined aquifers, the average discharge flux, and thus velocity, occurs at a point $\frac{l}{l_s} = 0.75$ above the base of the screen.

5.2.2 Non-Darcy Flow, Well Drawn Down to Top of Screen

When non-Darcy flow occurs near the well the discharge will be less than that for the comparable wholly Darcy flow case. Data which allows the discharge and free water surface level just outside the well to be calculated are given in Table 3. A typical plot of part of the data for $\frac{r_o}{h_o} = 2$ is given in Figure 43. It will be noted from the figure that the maximum discharge occurs for a value of $\frac{l_s}{h_o}$ (i.e. proportion of aquifer screened) which increases with $\frac{b}{a^2}$ from approximately 0.4 to 0.6. Maximum values of discharge and drawdown just outside the well are shown in Figure 44.

Typical free surface and base drawdown distributions are given in Figure 45.

A typical distribution of head within the aquifer is given in Figure 46.

Table 2 : Darcy Flow to a Partially Screened Well in an Unconfined Aquifer - Drawdown to Top of Screen

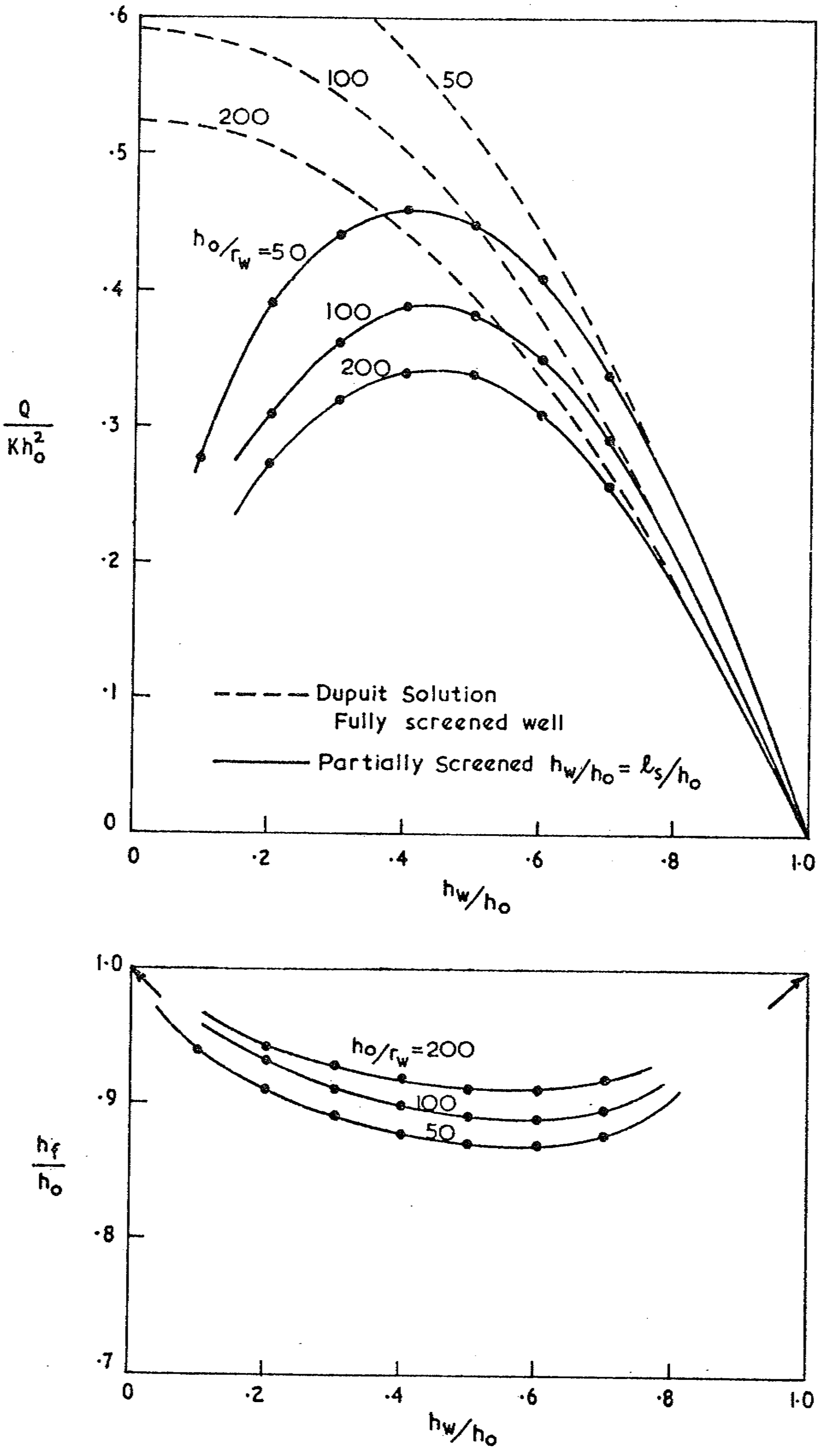
r_o/h_o	h_o/r_w	$h_w/h_o = l_s/h_o$					
		.2	.3	.4	.5	.6	.7

(a) Well performance - tabulated values of Q/Kh_o^2

r_o/h_o	h_o/r_w	.2	.3	.4	.5	.6	.7
2	200	.27	.32	.34	.34	.31	.26
	100	.31	.36	.39	.38	.35	
	50	.39	.44	.46	.45	.41	.34
4	200	.26	.30	.32	.31	.28	
	100	.30	.34	.36	.35	.31	
	50	.37	.41	.42	.40	.36	
8	200	.25	.28	.30	.29	.26	
	100	.29	.32	.33	.32	.29	
	50	.35	.38	.39	.37	.33	
16	200		.27	.28	.27		
	100		.30	.31	.30		
	50		.36	.36	.33		

(b) Free surface location at the well - tabulated values of h_f/h_o

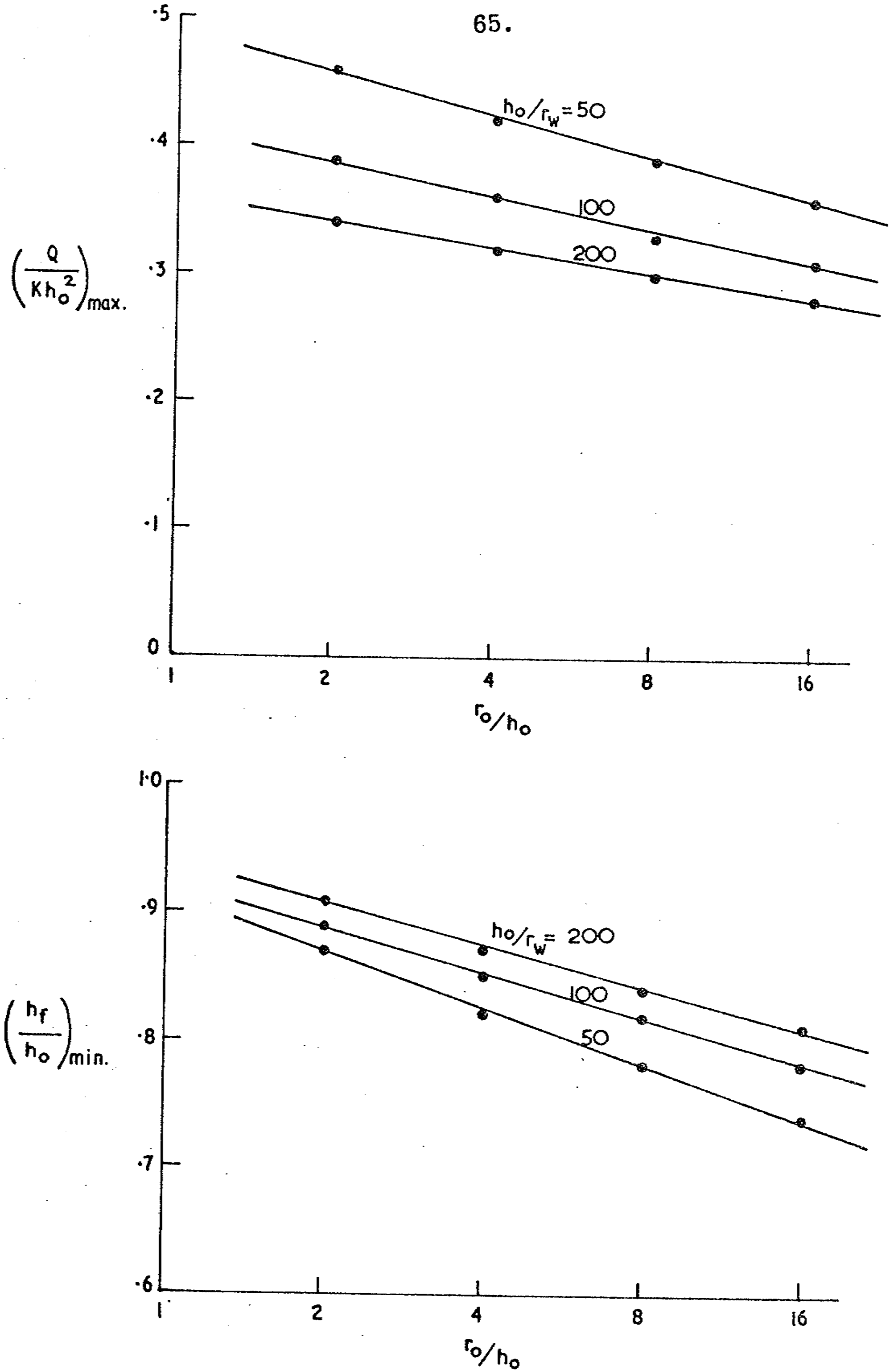
r_o/h_o	h_o/r_w	.2	.3	.4	.5	.6	.7
2	200	.94	.93	.92	.91	.91	
	100	.93	.91	.90	.89	.89	
	50	.91	.89	.88	.87	.87	
4	200	.91	.89	.88	.87	.87	
	100	.90	.87	.86	.85	.85	
	50	.86	.84	.83	.82	.83	
8	200	.88	.86	.84	.84	.84	
	100	.86	.83	.82	.82	.83	
	50	.82	.80	.78	.78	.79	
16	200		.82	.81	.81		
	100		.79	.78	.78		
	50		.75	.74	.74		



DARCY FLOW. $\ell_s = h_w$. $r_o/h_o = 2$

FIGURE 38: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER

TYPICAL EFFECTS FOR WELL DRAWDOWN TO TOP OF SCREEN - DARCY FLOW.



DARCY FLOW. $0{\cdot}4 < \ell_s/h_o = h_w/h_o < 0{\cdot}5$

FIGURE 39: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER.

MAXIMUM VALUES OF WELL DISCHARGE AND FREE SURFACE DRAWDOWN – NO SCREEN DEWATERING – DARCY FLOW

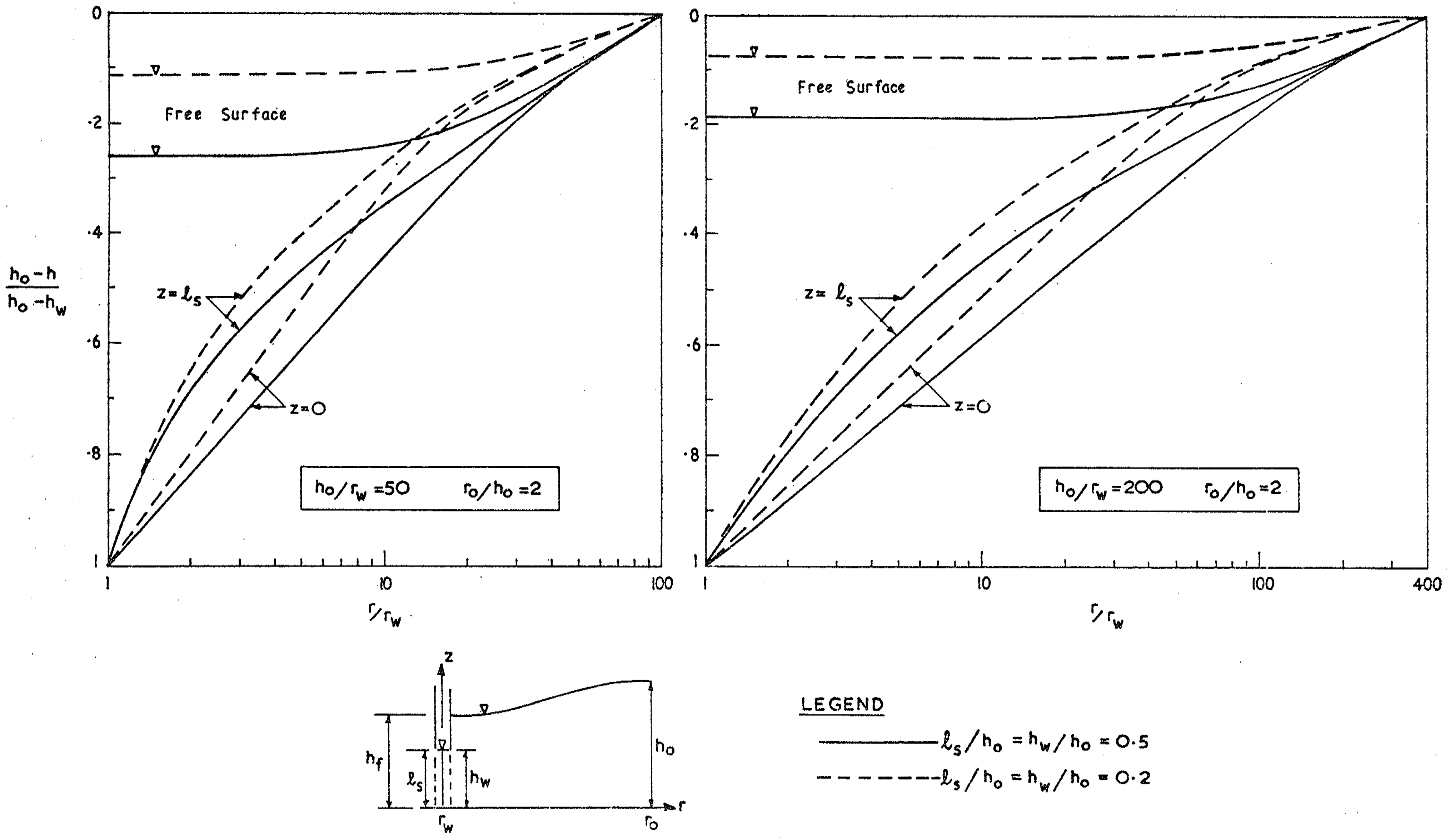


FIGURE 40: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER.
TYPICAL DRAWDOWN DISTRIBUTIONS FOR DARCY FLOW.

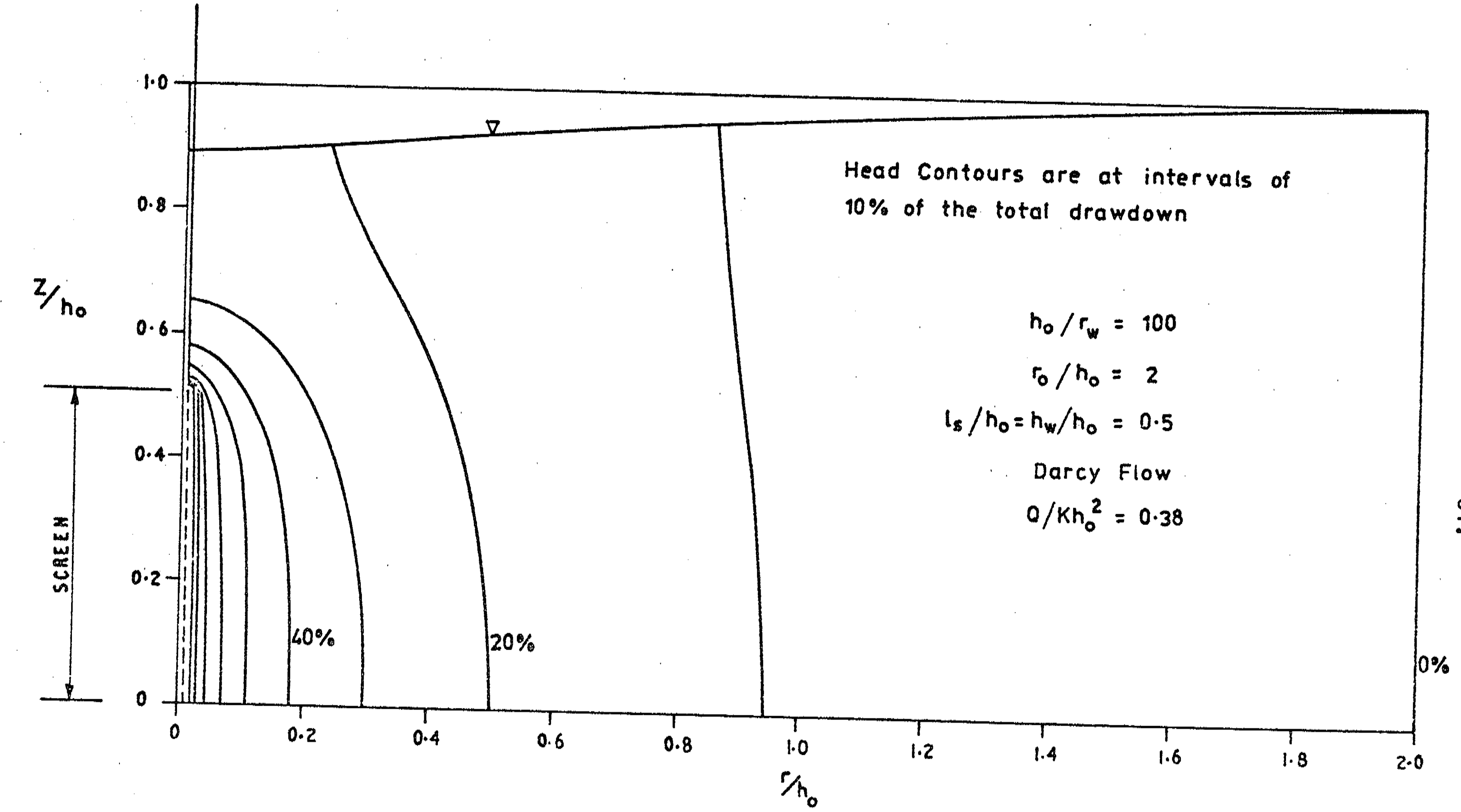


FIGURE 41: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER. TYPICAL HEAD DISTRIBUTION FOR DARCY FLOW.

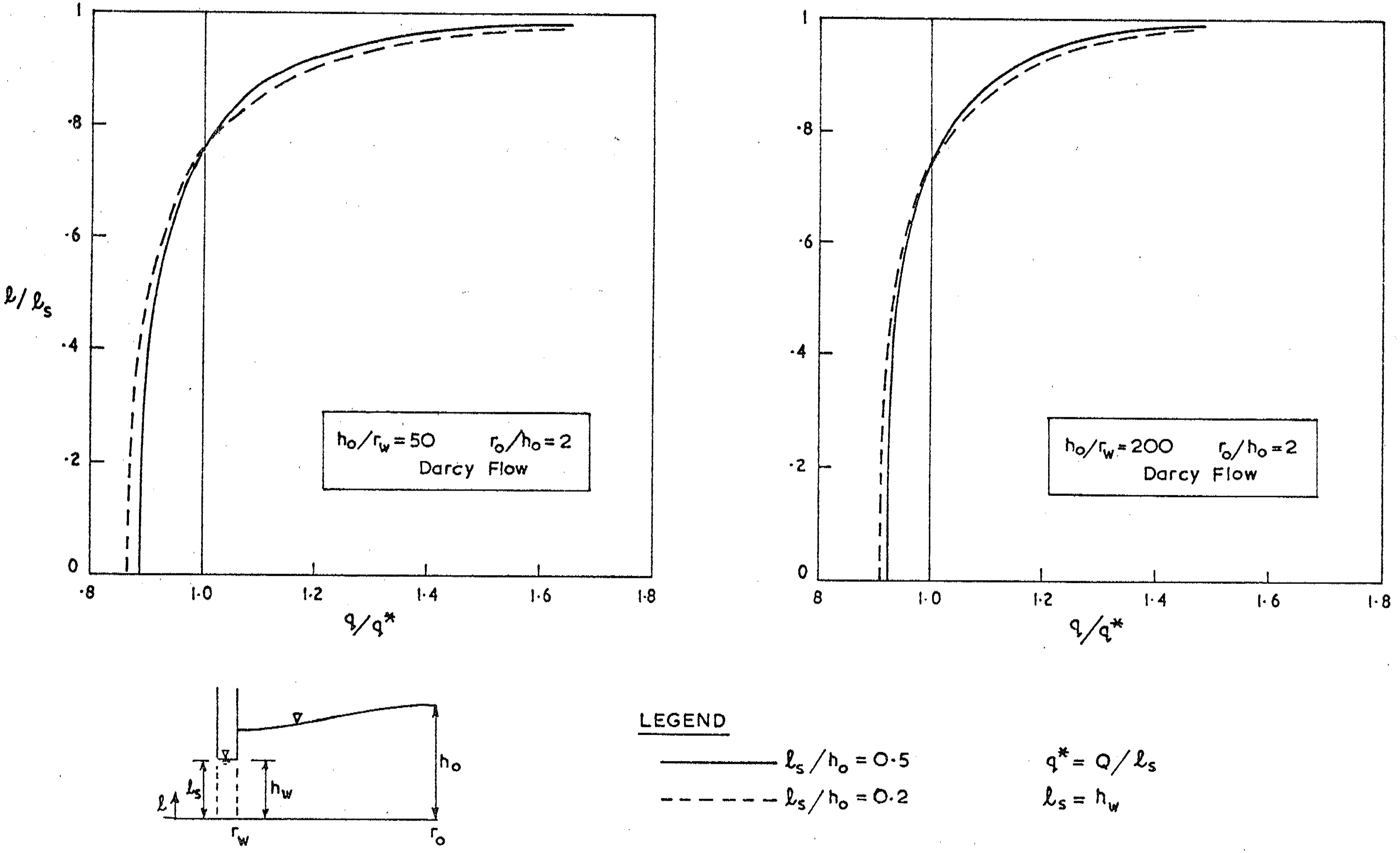
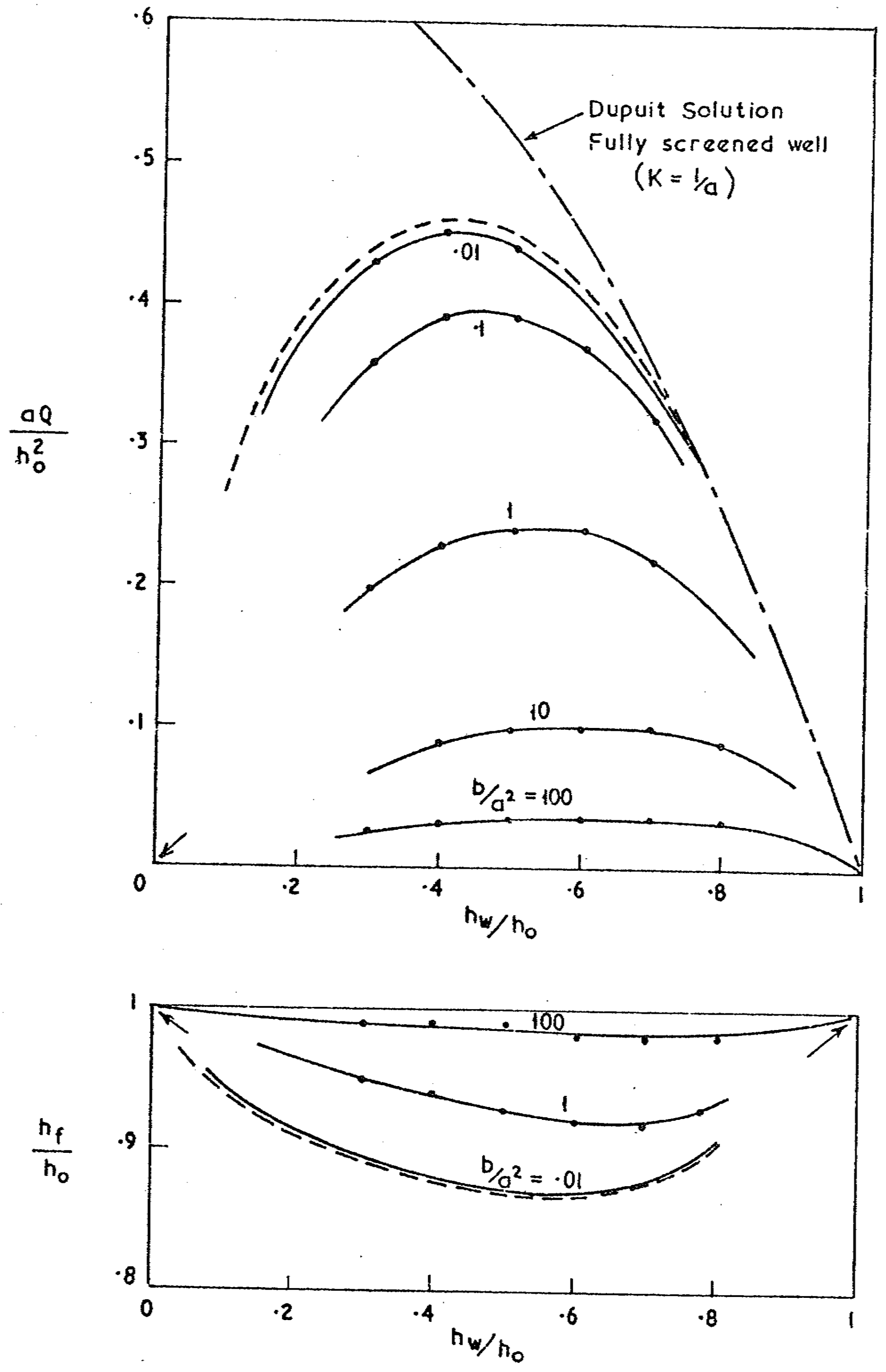


FIGURE 42: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER.
TYPICAL DISCHARGE FLUX DISTRIBUTIONS ALONG SCREEN - DARCY FLOW.



-----Darcy Flow Solutions K = 1/a

$r_o/h_o = 2$ $h_o/r_w = 50$ $\ell_s = h_w$

FIGURE 43: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER

TYPICAL EFFECTS FOR DRAWDOWN TO TOP OF SCREEN-NON LINEAR FLOW.

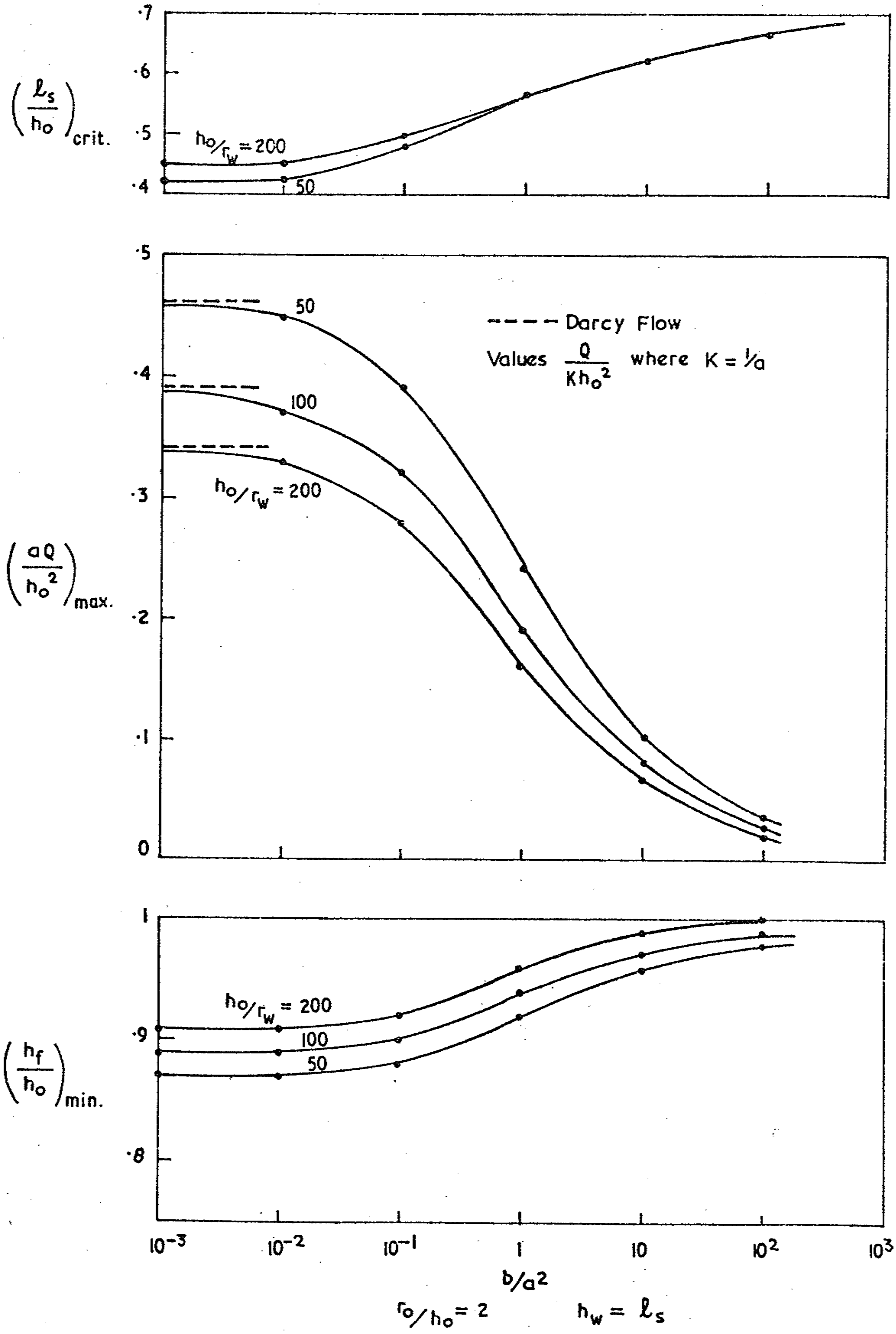


FIGURE 44: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER.

MAXIMUM VALUES OF WELL DISCHARGE AND FREE SURFACE DRAWDOWN - NO SCREEN DEWATERING - NON LINEAR FLOW

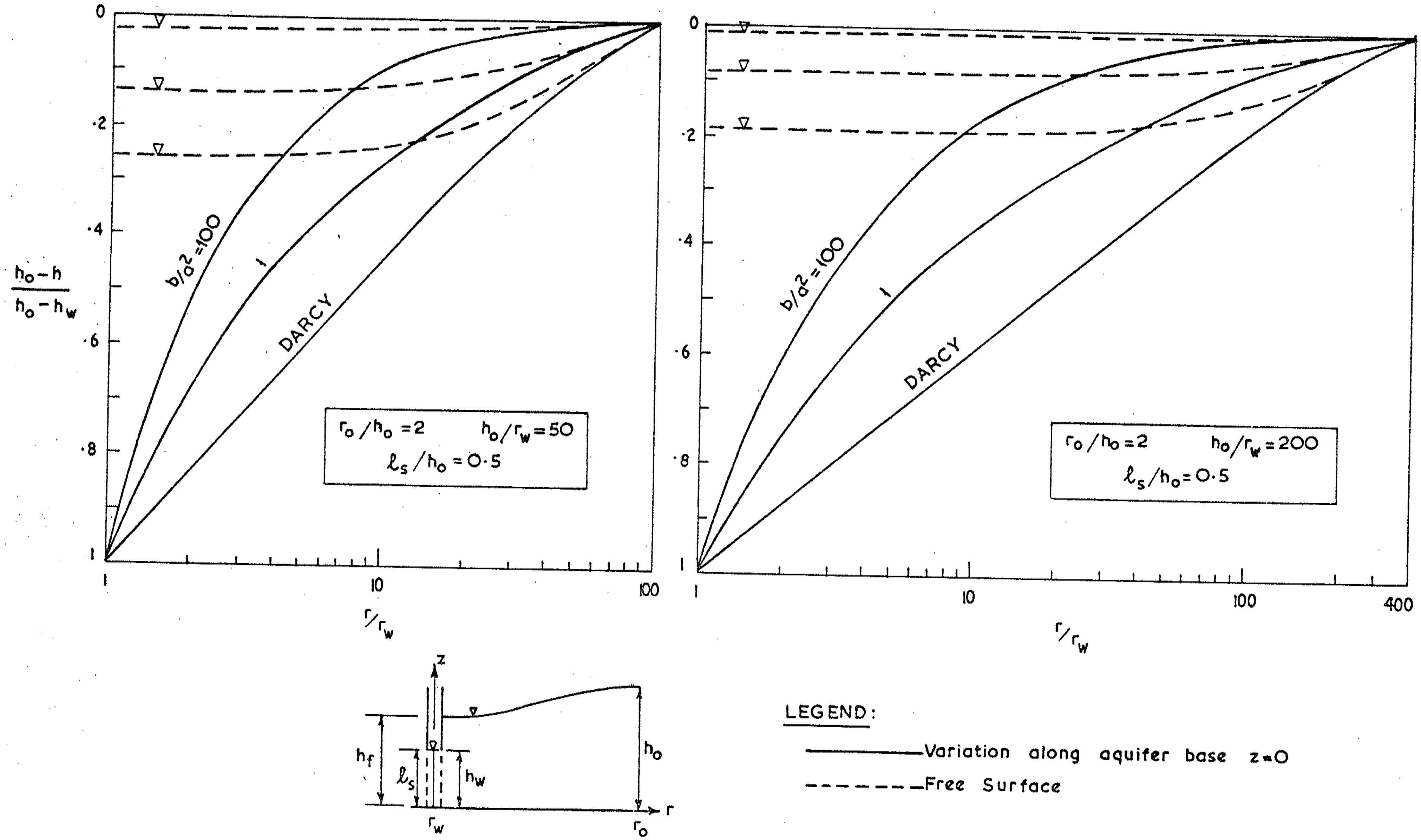


FIGURE 45: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER. TYPICAL DRAWDOWN DISTRIBUTIONS FOR NON LINEAR FLOW

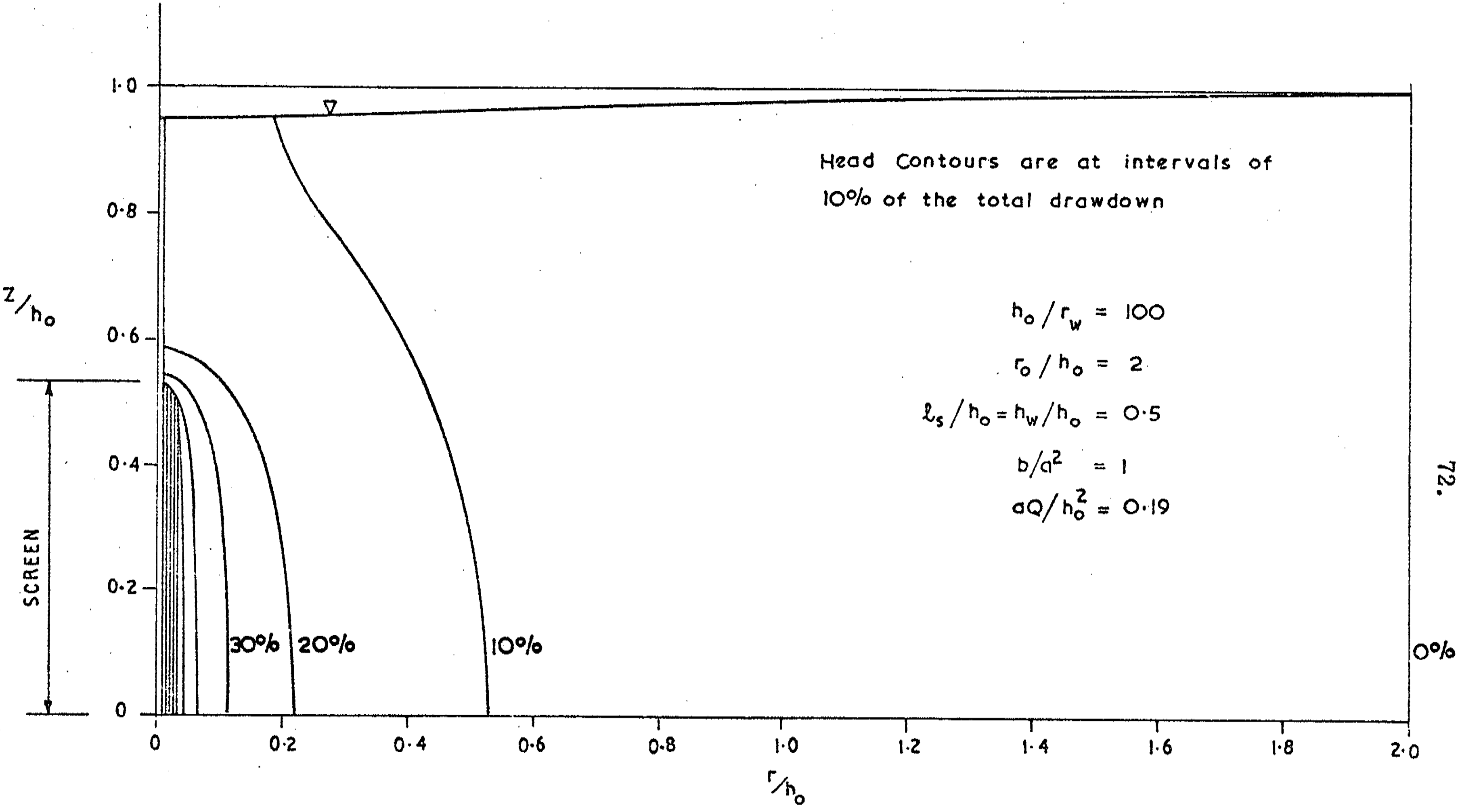


FIGURE 46: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER. TYPICAL HEAD DISTRIBUTION FOR NON LINEAR FLOW.

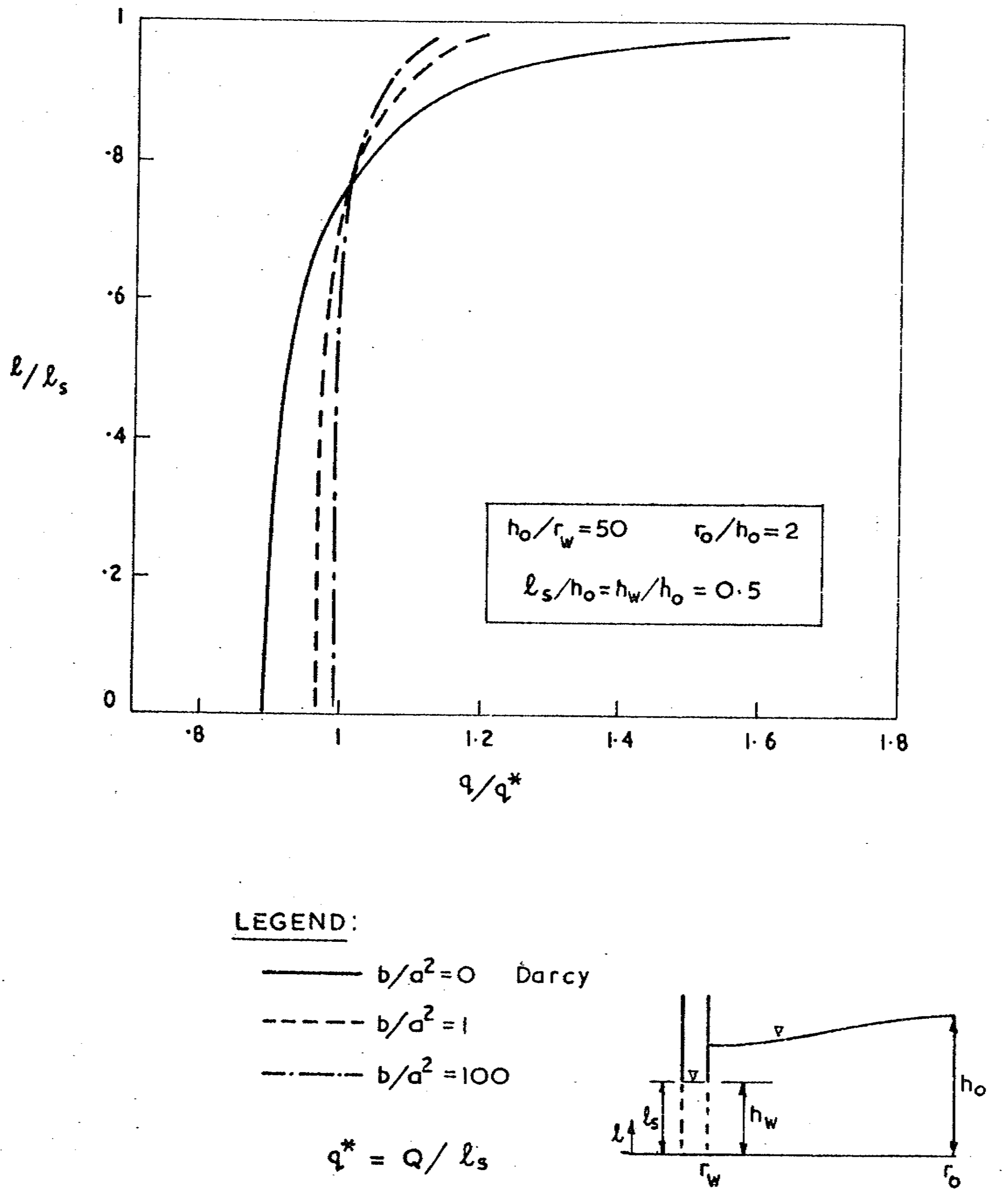


FIGURE 47: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER

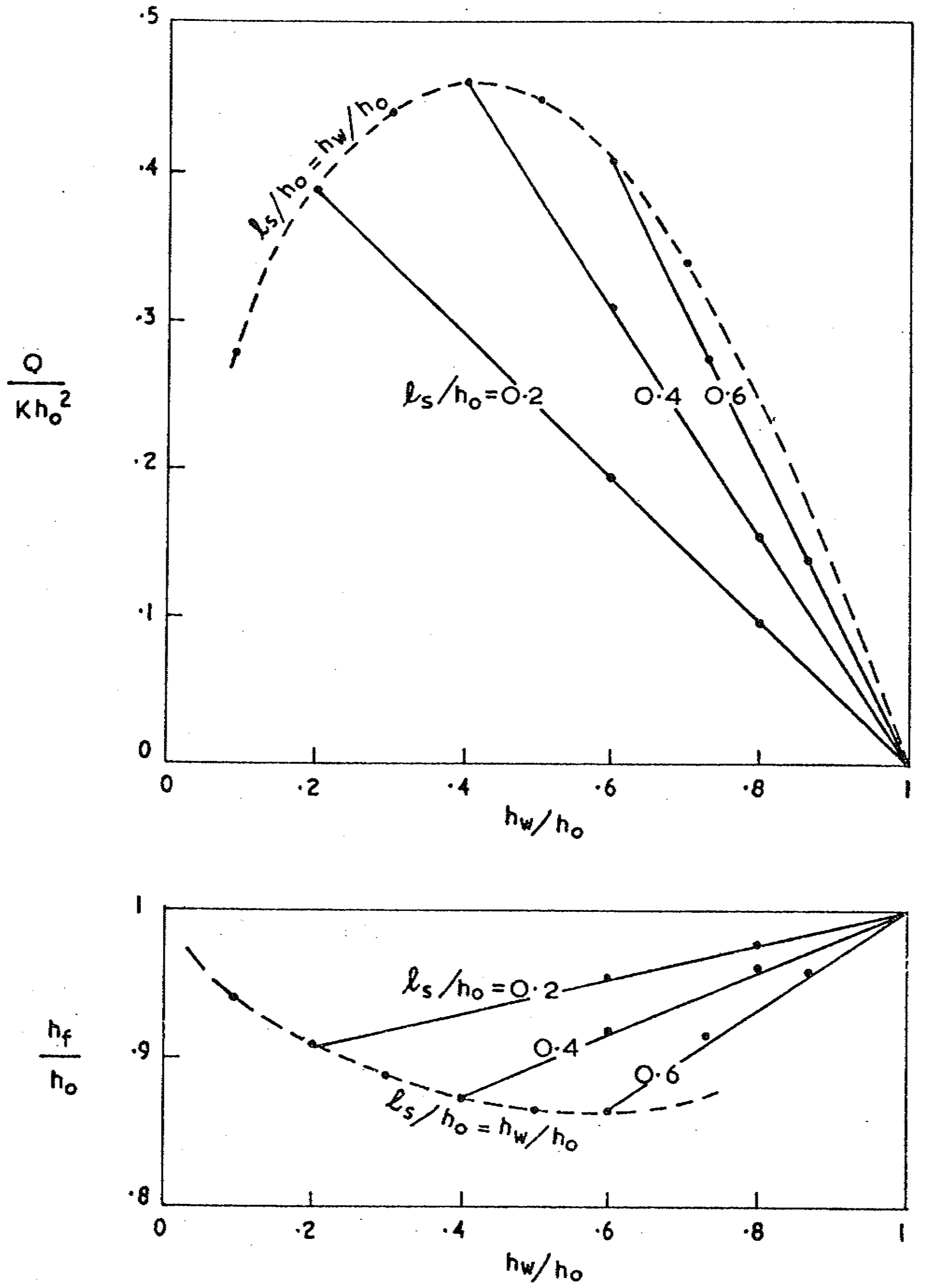
TYPICAL DISCHARGE FLUX DISTRIBUTIONS ALONG SCREEN - NON LINEAR FLOW

Table 3. Non-linear Flow to a Partially Screened Well in an Unconfined Aquifer-Drawdown to Top of Screen

			$h_w/h_o = l_s/h_o$						
r_o/h_o	h_o/r_w	b/a^2	.2	.3	.4	.5	.6	.7	.8
(a) Well Performance - Tabulated Values of $\frac{aQ}{h_o^2}$									
2	50	Darcy	.39	.44	.46	.45	.41	.34	
		.01		.43	.45	.44	.40		
		.1		.36	.39	.39	.37	.32	
		1		.20	.23	.24	.24	.22	
		10			.090	.099	.10	.10	.090
		100		.026	.031	.034	.036	.036	.033
2	100	Darcy	.31	.36	.39	.38	.35		
		.01		.35	.37	.37	.34		
		.1		.28	.31	.32	.31	.27	
		1		.15	.17	.19	.19	.18	
		10			.067	.074	.078	.077	.070
		100		.019	.023	.025	.027	.027	.025
2	200	Darcy	.27	.32	.34	.34	.31	.26	
		.01		.30	.32	.33	.30		
		.1		.24	.27	.28	.27	.24	
		1		.12	.14	.15	.16	.15	
		10			.054	.060	.064	.064	.058
		100		.015	.018	.020	.022	.022	.021
(b) Free Surface Location at the Well - Tabulated Values of h_f/h_o.									
2	50	Darcy	.91	.89	.88	.87	.87		
		.01		.89	.88	.87	.87		
		.1		.91	.89	.88	.88	.88	
		1		.95	.94	.93	.92	.92	
		10			.98	.97	.97	.96	.96
		100		.99	.99	.99	.98	.98	.98
2	100	Darcy	.93	.91	.90	.89	.89		
		.01		.91	.90	.89	.89		
		.1		.93	.92	.91	.90	.90	
		1		.96	.96	.95	.94	.94	
		10			.98	.98	.98	.97	.97
		100		.99	.99	.99	.99	.99	.99
2	200	Darcy	.94	.93	.92	.91	.91		
		.01		.93	.92	.91	.91		
		.1		.95	.94	.93	.92	.92	
		1		.98	.97	.97	.96	.96	
		10			1.00	.99	.99	.99	.99
		100		1.00	1.00	1.00	1.00	1.00	1.00

Table 4 : Partially Screened Well in an Unconfined Aquifer - Well Water Level Above the Screen - Tabulated Values of Q/Kh_o^2 and h_f/h_o

r_o/h_o	h_o/r_w	l_s/h_o	h_w/h_o	Q/Kh_o^2	h_f/h_o
2	50	0.2	0.2	.388	.908
			0.6	.194	.955
			0.8	.097	.978
			1	0	1
		0.4	0.4	.460	.874
			0.6	.308	.919
			0.8	.155	.962
			1	0	1
		0.6	0.6	.406	.863
			0.73'	.273	.915
			0.86'	.137	.960
			1	0	1
2	200	0.2	0.2	.268	.934
			0.6	.134	.967
			0.8	.067	.984
			1	0	1
		0.4	0.4	.337	.907
			0.6	.225	.939
			0.8	.113	.971
			1	0	1
		0.6	0.6	.311	.898
			0.73'	.208	.935
			0.86'	.104	.969
			1	0	1
8	50	0.2	0.2	.346	.824
			0.6	.175	.917
			0.8	.088	.960
			1	0	1
		0.4	0.4	.386	.782
			0.6	.260	.864
			0.8	.131	.936
			1	0	1
		0.6	0.6	.326	.795
			0.73'	.219	.874
			0.86'	.111	.941
			1	0	1



$r_o/h_o = 2$ $h_o/r_w = 50$

Darcy Flow

FIGURE 48: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER

NON-UTILIZATION OF FULL AVAILABLE DRAWDOWN – $h_w > \ell_s$ – DARCY FLOW

Typical discharge flux distributions along the screen are shown in Figure 47. As for wells in confined aquifers, the average value occurs at a point $\frac{l}{l_s} = 0.75$ along the screen from the base.

The effects of non-Darcy flow become negligible at $\frac{r_o}{h_o} = 2$, even for a value of $\frac{b}{a^2}$ as high as 100. Beyond $r = 2h_o$ the Dupuit equation (using $K = \frac{1}{a}$) may be used to describe the flow.

5.2.3 Wholly Darcy Flow, Well not Drawn Down to Top of Screen

If the maximum drawdown without screen dewatering is not utilised the discharge will be lower than that for the limiting case of drawdown to the top of the screen. A range of such cases was investigated using the computer programs. The results are presented in Table 4. A typical plot of the results for $\frac{h_o}{r_w} = 50$ is given in Figure 48. In all cases it was found that there was a linear variation of well discharge and free surface drawdown with $\frac{h_w}{h_o}$ between $h_w = l_s$ and $h_w = h_o$. Thus the values of discharge and free surface drawdown just outside the well may be predicted by linear proportioning from the data for drawdown to the top of the screen given in Section 5.2.1.

5.2.4 Non-Darcy Flow, Well Not Drawn Down to Top of Screen

This case has not been examined in detail but it is considered that an approximation to the discharge can be obtained by the method suggested in Section 5.2.3. Such estimates would be conservative. Individual cases can be checked by using the computer programs.

5.3 Well Screened above Base of Homogeneous Aquifer

Table 5 gives data from which well performance can be predicted if the screen is situated above the base of the aquifer and the well is drawn down to the top of the screen. Only wholly Darcy flow has been considered. The sketch below defines the problem and the symbols used.

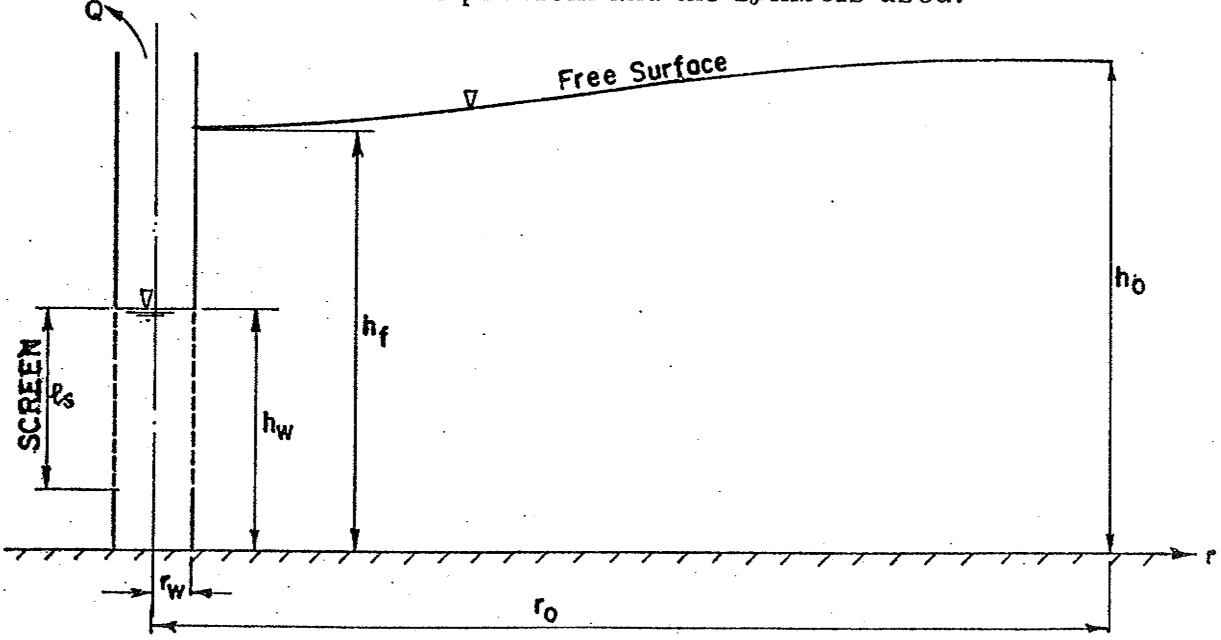
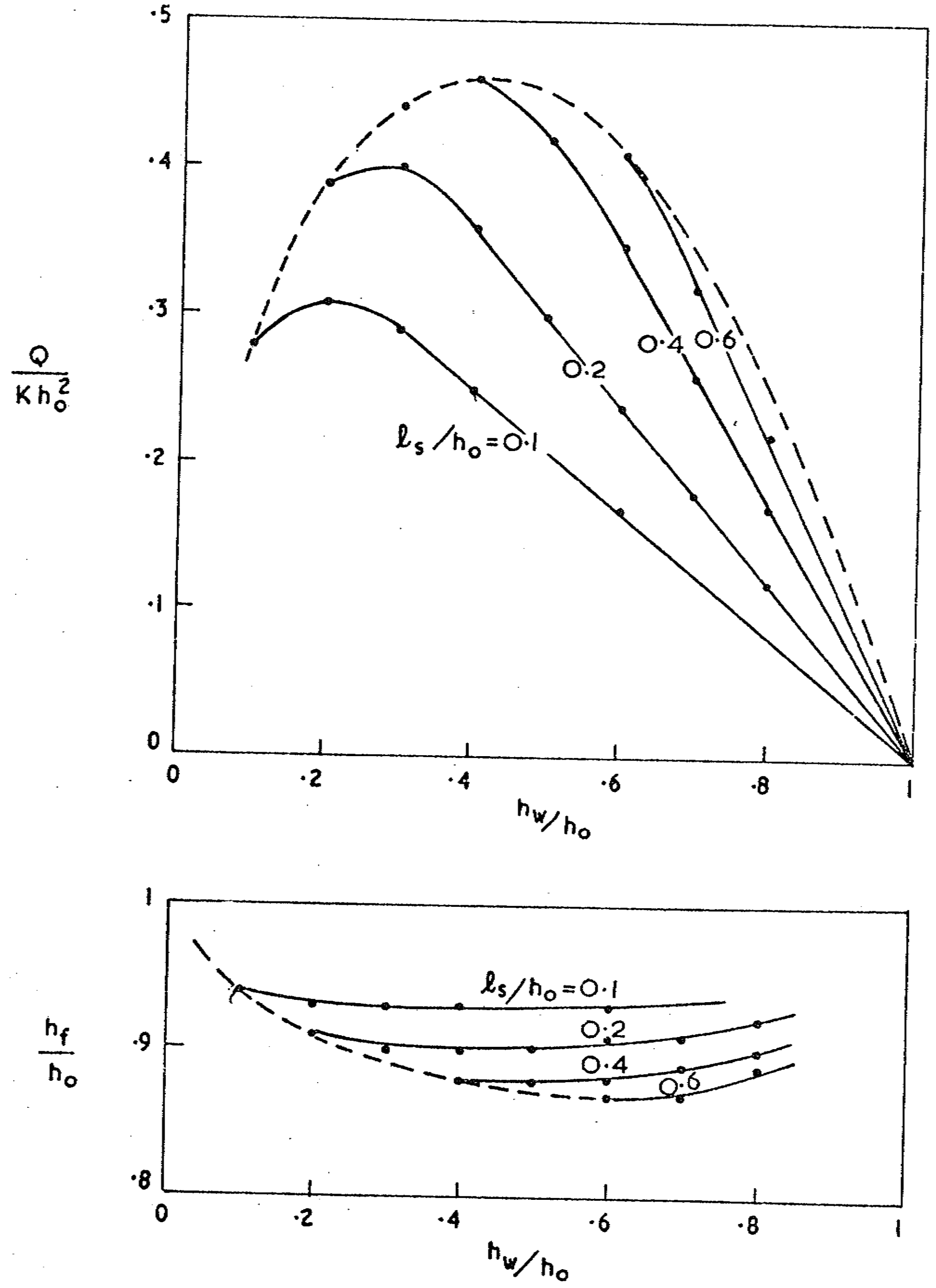


Table 5. Darcy Flow to Partially Screened Well in an Unconfined Aquifer - Well Screen Above Base of Aquifer.

r_o/h_o	h_o/r_w	l_s/h_o	h_w/h_o							
			.1	.2	.3	.4	.5	.6	.7	.8
(a) Well Performance - Tabulated Values of Q/Kh_o^2										
2	50	0.1	.28	.31	.29	.25		.17		
		0.2		.39	.40	.36	.30	.24	.18	.12
		0.4				.46	.42	.35	.26	.17
		0.6						.41	.32	.22
4	50	0.2		.37	.37	.33	.28	.22	.17	.11
		0.4				.42	.38	.31	.24	.16
		0.6						.36	.29	
2	200	0.2		.27	.28	.24	.21	.16	.12	.08
		0.4				.34	.31	.25	.19	.13
		0.6						.31	.25	.17
4	200	0.2		.26	.26	.23	.19	.16	.12	.08
		0.4				.32	.29	.24	.18	.12
		0.6						.28	.23	.15
(b) Free Surface Location at the Well - Tabulated Values of h_f/h_o										
2	50	0.1	.94	.93	.93	.93		.93		
		0.2		.91	.90	.90	.90	.91	.91	.92
		0.4				.88	.88	.88	.89	.90
		0.6						.87	.87	.89
4	50	0.2		.86	.85	.86	.87	.88	.89	.90
		0.4				.83	.83	.84	.86	.88
		0.6						.83	.84	.86
2	200	0.2		.94	.93	.93	.94	.94	.94	.95
		0.4				.92	.92	.92	.93	.94
		0.6						.91	.92	.92
4	200	0.2		.91	.90	.91	.92	.92	.93	.94
		0.4				.88	.88	.89	.90	.92
		0.6						.87	.89	.91



----Solution for screen in base $(\ell_s = h_w)$

$r_o/h_o = 2$ $h_o/r_w = 50$

FIGURE 49: PARTIALLY SCREENED WELL IN AN UNCONFINED AQUIFER

WELL SCREEN ABOVE BASE OF AQUIFER - DARCY FLOW

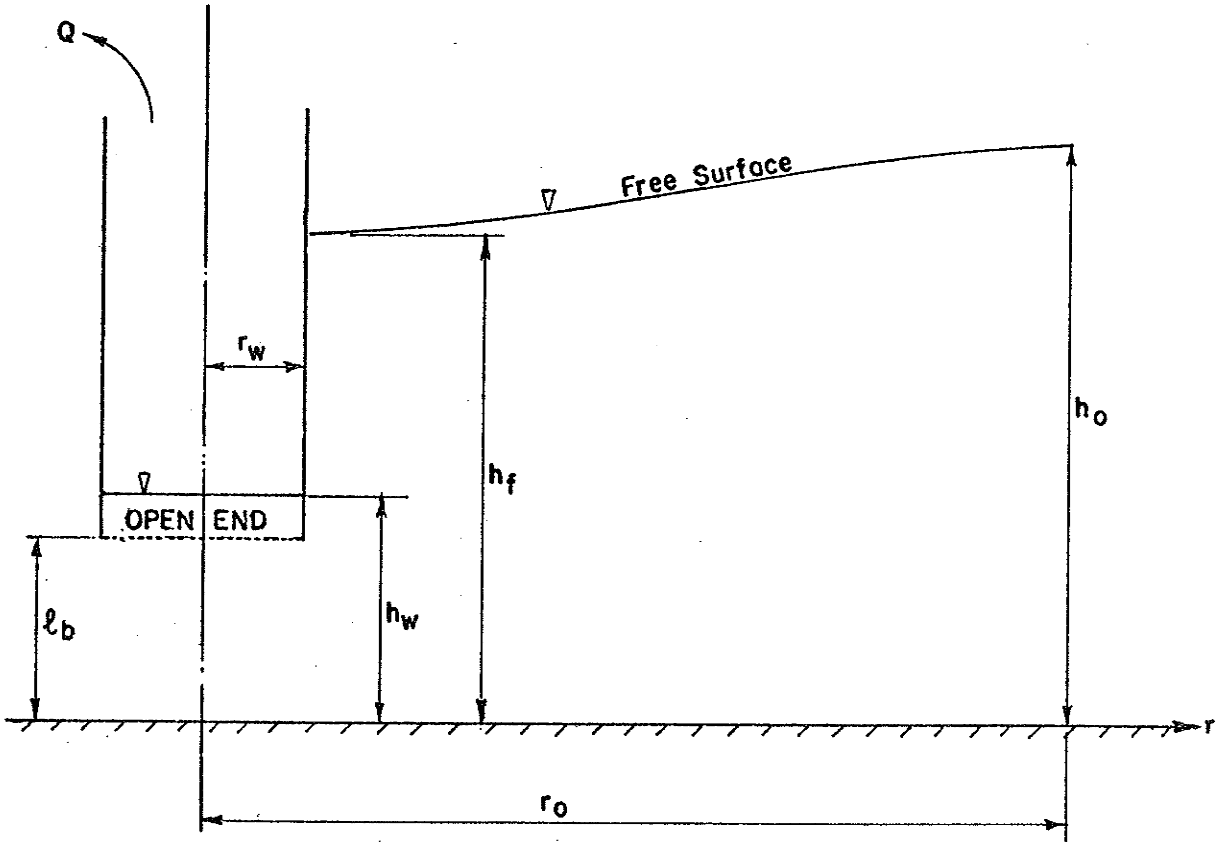
Table 6: Bottom Entry Large Diameter Well in an Unconfined Aquifer

r_o/h_o	h_o/r_w	Flow b/a^2	l_b/h_o	h_w/h_o				
				1/8	1/4	1/2	3/4	1
(a) Well Performance - Tabulated Values of Q/Kh_o^2 $(K = 1/a)$								
2	5	0(Darcy)	h_w/h_o	.81	.81	.58	.29	0
	10			.48	.48	.32	.16	0
	20			.29	.27	.19		0
2	5	1	h_w/h_o	.38	.41	.37	.20	0
		10		.15	.18	.18	.093	0
		100		.052	.057	.048	.034	0
2	10	1	h_w/h_o	.18	.18	.16	.088	0
		10		.070	.068	.060	.038	0
		100		.023	.023	.019	.014	0
2	10	0(Darcy)	1/8	.48	.41	.27	.14	0
			1/4		.48	.31	.15	0
			1/2			.32	.17	0
2	5	0(Darcy)	1/8	.81	.69	.46	.23	0
			1/4		.81	.54	.28	0
			1/2			.58	.34	0
4	5	0(Darcy)	h_w/h_o	.72	.71	.50	.25	0
8	5	0(Darcy)	h_w/h_o	.63	.62	.45	.22	0
(b) Free Surface Location at the Well - Tabulated Values of h_f/h_o								
2	5	0(Darcy)	h_w/h_o	.83	.82	.83	.85	1
	10			.90	.89	.90	.91	1
	20			.93	.94	.95		1
2	5	1	h_w/h_o	.92	.91	.90	.91	1
		10		.96	.95	.94	.95	1
		100		.98	.98	.98	.98	1
2	10	1	h_w/h_o	.96	.96	.95	.95	1
		10		.99	.99	.98	.98	1
		100		.99	.99	.99	.99	1
2	10	0(Darcy)	1/8	.89	.91	.94	.97	1
			1/4		.88	.93	.97	1
			1/2			.90	.95	1
2	5	0(Darcy)	1/8	.83	.86	.91	.96	1
			1/4		.82	.88	.94	1
			1/2			.83	.91	1
4	5	0(Darcy)	h_w/h_o	.74	.73	.75	.84	1
8	5	0(Darcy)	h_w/h_o	.66	.65	.71	.83	1

Figure 49 is a plot of part of the data of Table 5 for $\frac{r_o}{h_o} = 2$ and $\frac{h_o}{r_w} = 50$. It will be seen that if $\frac{l_s}{h_o} < 0.4$ the maximum discharge for a given length of screen is obtained by positioning the screen midway between the base of the aquifer and a point 0.4 h_o above the base.

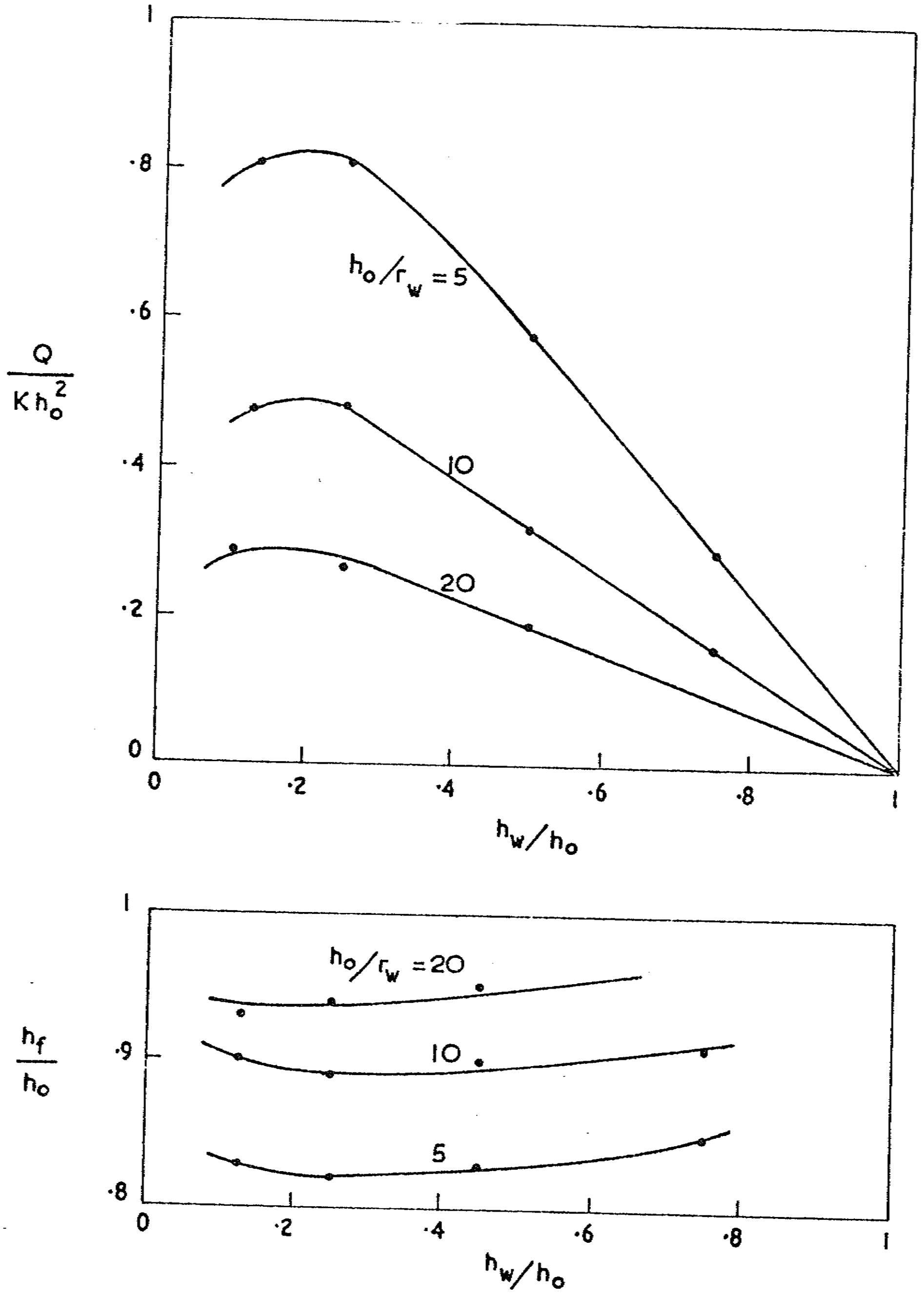
5.4 Bottom Entry, Large Diameter Wells

In shallow aquifers it may be a practical proposition to construct large diameter wells up to 2 metres in diameter with open bottoms. The sketch below shows the configuration considered.



Data to allow the prediction of the performance of such wells for various drawdowns is provided in Table 6. Typical plots showing part of the data for wells drawn down to the bottom are given in Figure 50 for wholly Darcy flow and in Figure 51 for non-Darcy flow. For Darcy flow the maximum discharge occurs when $1/8 < \frac{l_b}{h_o} < 1/4$. For non-Darcy flow the value of $\frac{l_b}{h_o}$ at which maximum discharge occurs increases with increasing non-linearity as measured by the value of $\frac{b}{a^2}$.

Typical drawdown distributions are given in Figure 52.



$r_o/h_o = 2$ $\ell_b = h_w$ Darcy Flow

FIGURE 50: BOTTOM ENTRY LARGE DIAMETER WELL IN AN UNCONFINED AQUIFER

TYPICAL EFFECTS FOR DRAWDOWN TO BASE OF WELL - DARCY FLOW

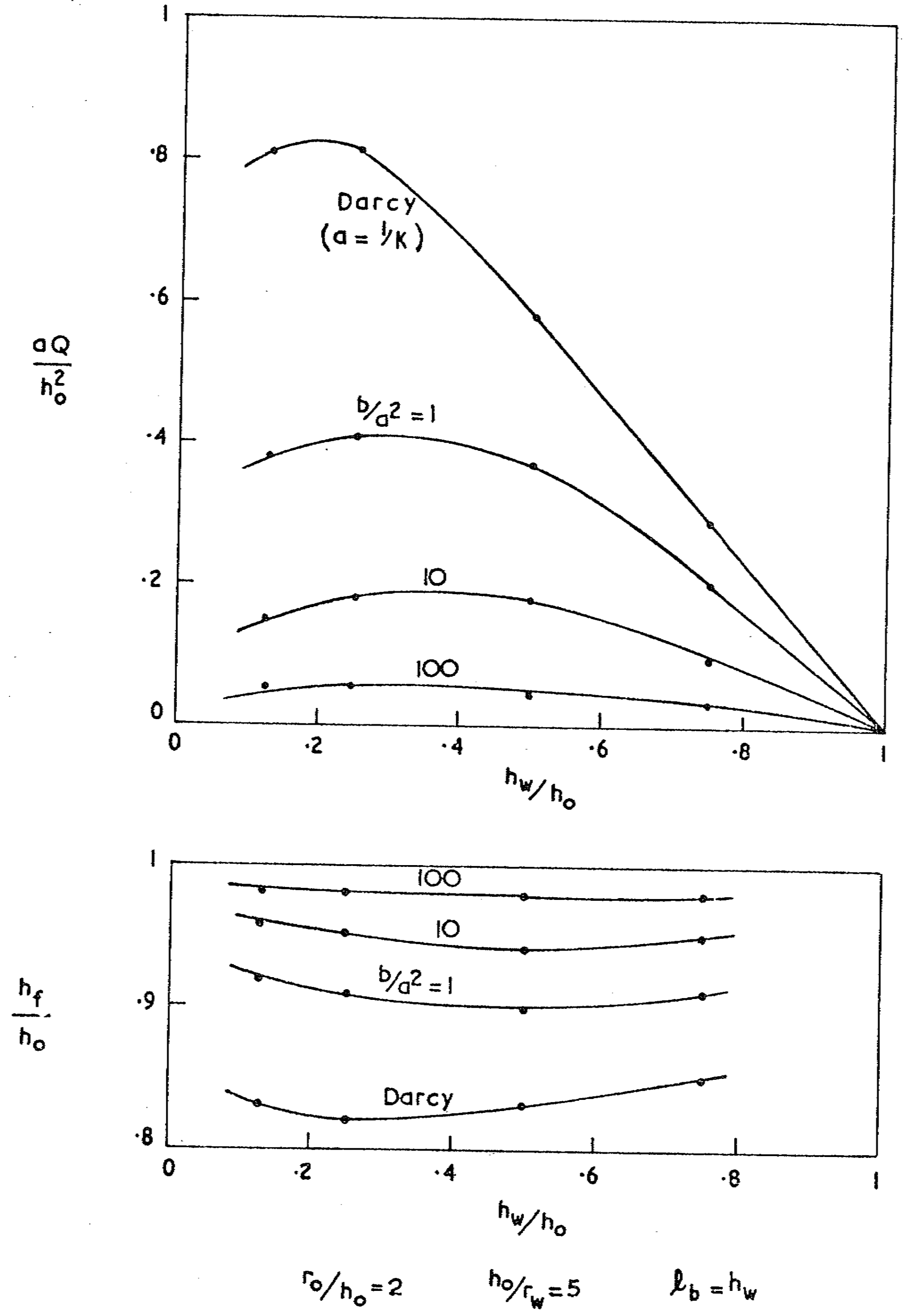


FIGURE 51: BOTTOM ENTRY LARGE DIAMETER WELL IN AN UNCONFINED AQUIFER

TYPICAL EFFECTS FOR DRAWDOWN TO BASE OF WELL - NON LINEAR FLOW

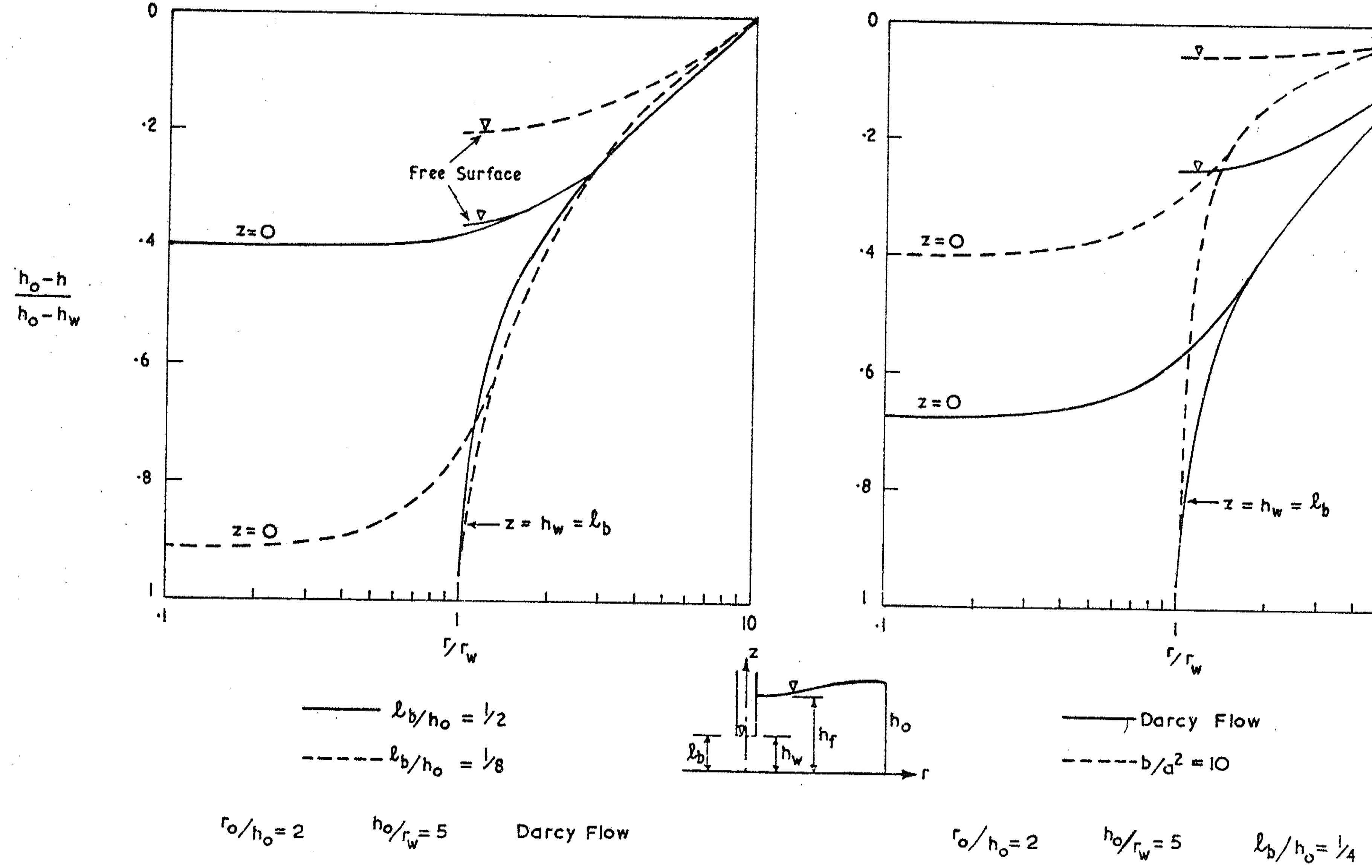


FIGURE 52: BOTTOM ENTRY LARGE DIAMETER WELL IN AN UNCONFINED AQUIFER TYPICAL DRAWDOWN DISTRIBUTIONS

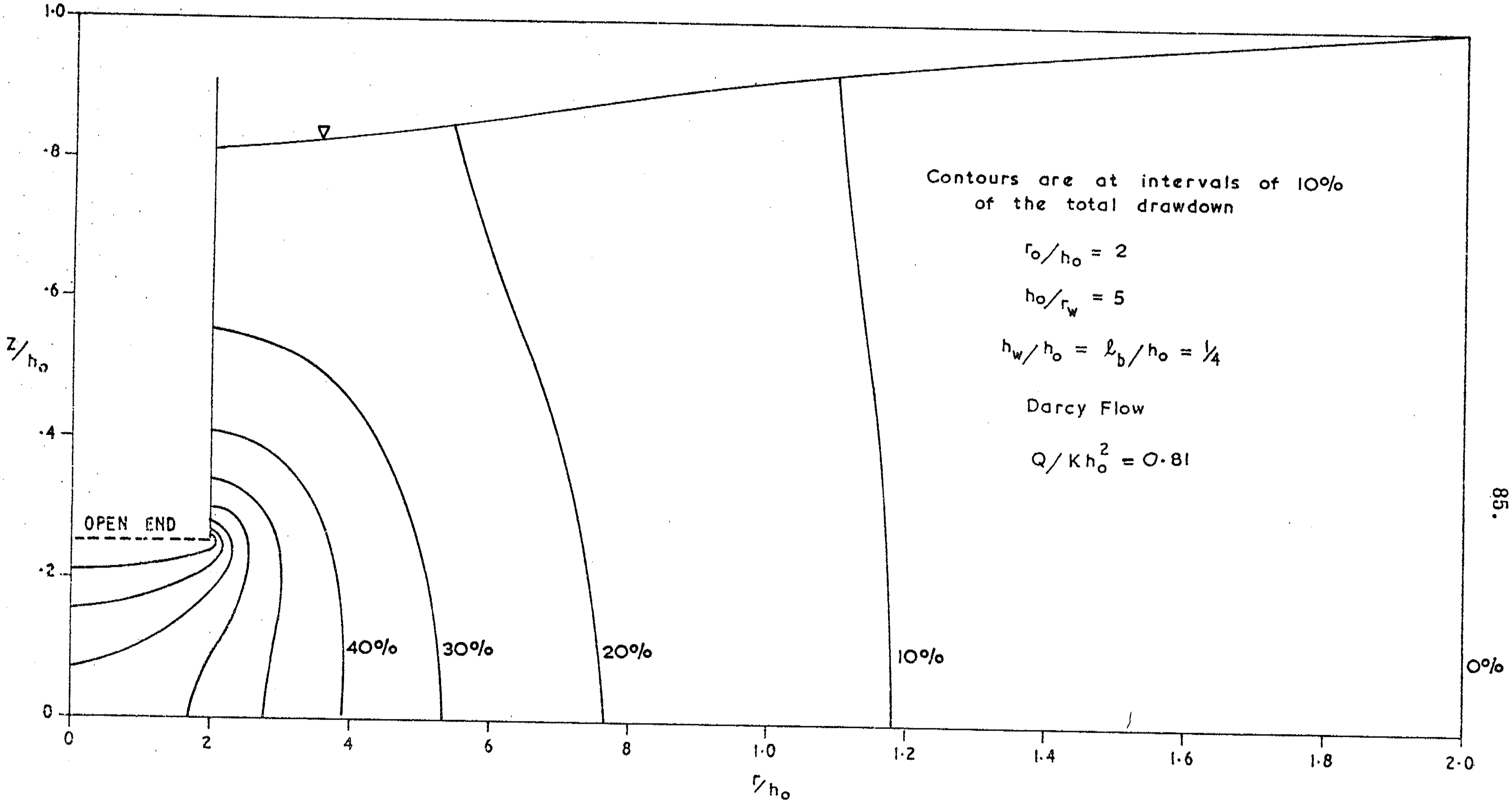
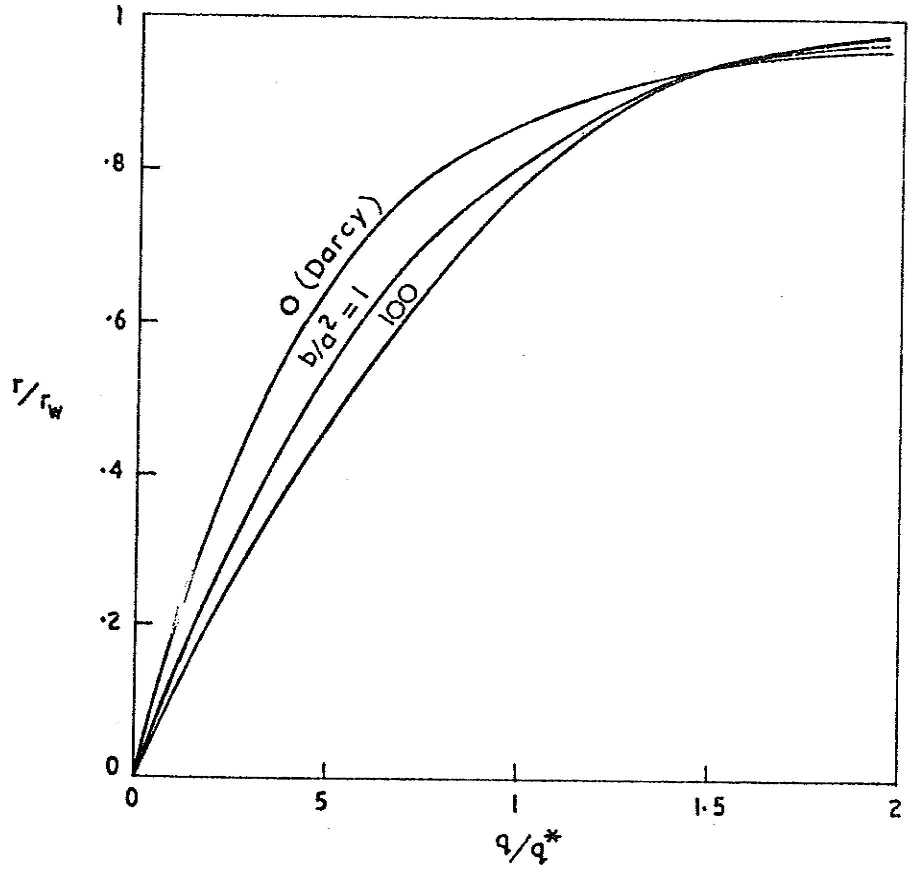
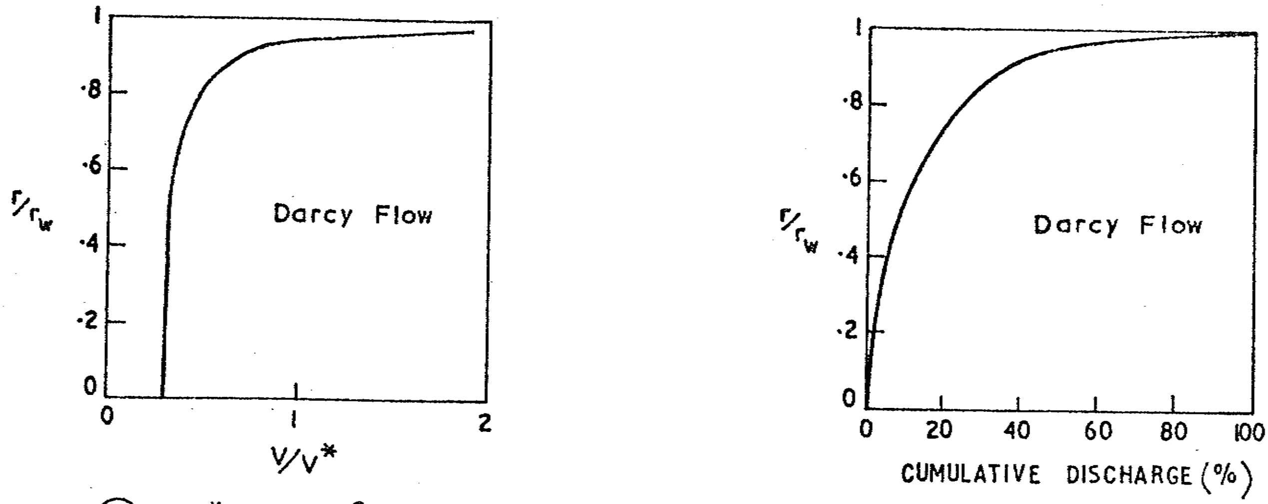


FIGURE 53: BOTTOM ENTRY LARGE DIAMETER WELL IN AN UNCONFINED AQUIFER TYPICAL HEAD DISTRIBUTIONS FOR DARCY FLOW



ⓐ $q^* = Q/r_w$



ⓑ $V^* = Q/\pi r_w^2$

ⓒ

$r_o/h_o = 2$, $5 \leqslant h_o/r_w \leqslant 20$, $\ell_b/h_o > 1/8$

FIGURE 54: BOTTOM ENTRY LARGE DIAMETER WELL IN AN UNCONFINED AQUIFER.
DISTRIBUTION OF DISCHARGE FLUX, VELOCITY AND CUMULATIVE WELL DISCHARGE ALONG BOTTOM ENTRY SECTION.

A typical distribution of head throughout the aquifer is given in Figure 53.

Figure 54 shows typical discharge flux distributions across the base of the well. The maximum discharge flux, and thus velocity, is of the order of twice the average.

List of References

1. Cox, R.J. (1976) "A study of near-well groundwater flow and the implications in well design". Ph.D. Thesis, School of Civil Engineering, University of New South Wales.

2. Dudgeon, C.R. et al (1973) "Hydraulics of flow near wells in unconsolidated sediments. Vol. 2.Field studies" Univ. of New South Wales, Water Research Lab. Report No. 126.

3. Dudgeon, C.R., Cox, R.J. (1975) "Drilling mud invasion of unconsolidated aquifer materials". Australian Water Resources Council Technical Paper No. 17.

4. Dudgeon, C.R., Huyakorn, P. (1975) "Effects of near-well permeability variation on well performance" Australian Water Resources Council Technical Paper No. 18.

5. Huyakorn, P. (1974) "Finite element solution of two-regime flow towards wells" Univ. of New South Wales, Water Research Lab. Report No. 137 (Ph.D. thesis).

6. Huyakorn, P., Dudgeon, C.R. "Finite element programs for analysing flow towards wells". Univ.of New South Wales, Water Research Lab. Report No. 135.

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