SEAWATER INTRUSION STUDIES FOR COASTAL AQUIFERS

By

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THESIS

Submitted in partial fulfilment of the
requirement for the degree

Master of Science in Agricultural Engineering

Faculty of Agricultural Engineering
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Tavanur, Malappuram
1988

DECLARATION

I hereby declare that this thesis entitled "Seawater intrusion studies for coastal aquifers" is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

Tavanur,
23/11/ 1988.

Abraham
SALEY ABRAHAM

CERTIFICATE

Certified that this thesis entitled "Seawater intrusion studies for coastal aquifers" is a record of research work done independently by Kum. SALEY ABRAHAM under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to her.

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SYMBOLS AND ABBREVIATIONS

b	Thickness of aquifer
cm	centimetre (s)
D	Depth of aquifer below mean sea level
D_o	Depth of aquifer at outflow face
Ec	Electrical conductivity
eq	Equivalent
g	gram (s)
h	height of water above mean sea level
h_1 & h_2	Height of water levels from the impermeable stratum
h_u	Elevation of surface source level
i, j	Suffixes indicating nodal points
k	Coefficient of permeability
km	kilometre(s)
L	Length of interface
L_1 & L_2	Distances of the wells from the coast
m	metre(s)
n	Porosity of the aquifer
ppm	parts per million
q	Seaward fresh water flow
Q_I	Initial aquifer discharge per metre width
Q_F	Final aquifer discharge per metre width

Q_p	Maximum pumping rate from the aquifer
SAR	Sodium Adsorption Ratio
w	Complex potential
x, y	Co-ordinates of interface
X	Distance from the coast
Y	Depth of interface below mean sea level
Y_o	Depth of interface at outflow face
Z	Thickness of each layer of soil
α	Excess density ratio
β	Aquifer constant
γ_f	Specific weight of fresh water
γ_s	Specific weight of seawater
ϕ	Velocity potential
ψ	Stream potential
ρ_f	Density of fresh water
ρ_s	Density of sea water
μ	micro

Introduction

INTRODUCTION

Kerala State has a coast line of 560 kilometres extending from south to north with a huge reserve of groundwater. Since groundwater is a replenishable resource, there is ample scope for its development. Trichur district is having a coastal length of 66 kilometres. The surface geological features of Trichur coastal belt mainly consists of fine sand, medium to coarse sand and clay.

In coastal areas, fresh water requirements for industry, agriculture and domestic uses are often met from ground water resources as the water from the surface sources are either polluted or insufficient. Efficient management and design of ground water systems call for accurate prediction of the process of sea water intrusion into coastal aquifers. Studies regarding the availability of fresh ground water and its protection from sea water has become acute during the current century all over the world.

Contamination of surface and groundwater by intrusion of salinity from the sea is a common problem in the coastal belt of Kerala. Most of the common crops cannot grow under saline conditions and thus agricultural productivity of coastal regions is affected. The paddy fields of Kuttanad region is affected by the ingress of sea water into fresh water either through tidal surges or through sub soil seepage. The sea water intrusion structures built in the Kuttanad region help to prevent the flow of saline water into the rivers and backwaters to some extent.

When coastal aquifers come in contact with the ocean freshwater is discharged into the ocean. Sometimes the seaward flow of groundwater decreases or even gets reversed with the increased extraction of groundwater. Thus the seawater has a tendency to enter into the aquifers. This phenomenon is called seawater intrusion. This occurs due to density currents and tidal action. The density currents occur due to the density differences between seawater and fresh water. The problem of salinity intrusion can be classified into two groups according to the nature of occurrence. They are (1) salinity intrusion of surface waters such as that through the estuarine rivers (2) salinity intrusion into coastal aquifers. The present study deals with the latter.

Under natural conditions the slope of the water table is towards the sea, since the flow of fresh water towards the sea must come into balance with the supply from the rainfall infiltration. When steady conditions prevail in the ground water system at a constant sea level, a state of equilibrium will be established between the sea water and the fresh water flowing through the aquifer which will lead to the formation of a steady sea water - fresh water interface. However, any change in the mean sea level or in the fresh water discharge due to excessive withdrawal or recharge will create a change in the general equilibrium conditions causing the interface to move to a new equilibrium position through a transient stage. Seasonal fluctuations in sea level

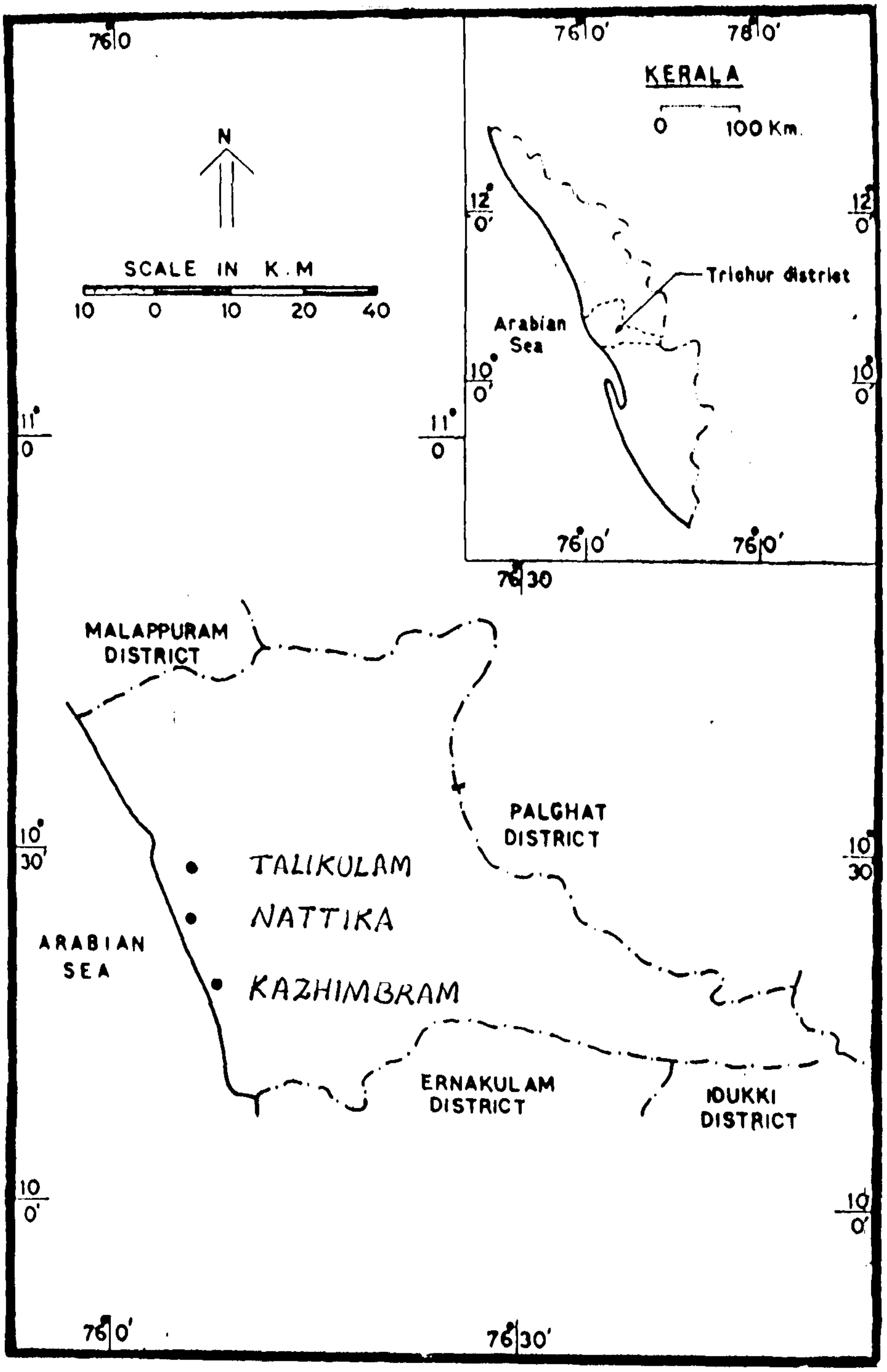


FIG.1.1. MAP OF TRICHUR DISTRICT SHOWING THE COASTAL LENGTH.

also contribute to the unsteadiness of the interface. The increase of fresh water discharge will cause a seaward movement and a reduction in discharge will cause a landward movement. The former is called as a retreating interface and latter as an advancing interface. The advancing interface is a common occurrence as the exploitation of ground water resources by large scale pumping is being attempted in various parts of the world. In such cases it becomes all the more important to predict the rate and extent of movement of the interface.

The present study was conducted in three villages near the coast line of Trichur district namely Nattika, Tallikulam and Edamuttom. The main objective of the study was to check whether there is sea water intrusion problem in the present situation and if not find the chances of intrusion with further exploitation of ground water. The study enables one to predict the safe rate at which the available ground water resources at a site can be exploited without any fear of salt water intrusion.

Review of literature

REVIEW OF LITERATURE

One of the earliest reports of sea water intrusion was published by Braithwaite (1850). He described the increasing salinity of waters pumped from wells in London and Liverpool, England. (Todd, 1959)

Ghyben (1889) conducted studies on sea water intrusion in the Dutch coast and developed a theoretical relation. The same relation was presented independently by Herzberg (1901) from observation at the German coast. The relation was derived from the assumption that, at equilibrium condition, the interface was steady and the pressure at a point on it from either side was same. A second assumption was that hydrostatic pressure distribution exist in the porous medium. These two assumptions lead to a significant relation, $Y_o = S_o / \alpha$ where Y_o is the depth of interface below mean sea level, S_o is the height of the free surface above mean sea level and α is the excess density ratio. This static equilibrium theory was used in developing basic equation for more complex aspects of the intrusion problem. (Todd, 1959)

Brown (1925) had checked the validity of Ghyben-Herzberg static equilibrium theory from field investigations and established the usefulness of the theory as a first approximation for further studies. He reported that fresh water discharge could be observed on the coastal line above mean sea level. The concept accepted was that the actual interface was below the one suggested by Ghyben-Herzberg.

Hubbert (1940) considered a dynamic state of liquids for developing equation for intrusion. He reported that velocity increased as flow approached the outlet due to the converging nature of the interface. He added that the interface had a concave shape with respect to the fresh water.

Todd (1955) had done much work on the problem of sea water intrusion at the University of California. This studies included a comprehensive literature research on sea water intrusion and its control. He derived an equation for seaward fresh water flow.

$$q = \frac{1}{2} \left(\frac{\gamma_s - \gamma_f}{\gamma_f} \right) \frac{Kb^2}{L} \qquad 2.1$$

where q is the seaward fresh water flow, γ_f and γ_s are fresh and salt water densities respectively. L is the length of intrusion and b is the thickness of the aquifer.

He suggested five methods for controlling intrusion. The methods were

(a) reduction or rearrangement of pattern of pumping draft

(b) direct recharge

(c) development of a pumping trough adjacent to the coast

(d) maintenance of a fresh water ridge above sea level alone the coast

(e) construction of artificial subsurface barriers.

Glover (1959) assumed no flow in salt water for an abrupt interface between the fresh and salt water and gave an equation of the interface for an aquifer with a horizontal outflow face.

$$Y^2 = \frac{2|Q|X}{\alpha K} + [\frac{|Q|^2}{\alpha K}] \qquad 2.2$$

Where Y is the depth of the interface below mean sea level, Q is the fresh water discharge, X is the distance from the coast to the interface, α is the excess density ratio and K is the effective coefficient of permeability.

Henry (1959) gave a theoritical treatment of steady state problem of sea water intrusion in a confined aquifer with and without dispression and derived theoritical equations for the shape and location of the interface and for the boundary conditions. The equation for confined aquifer with a horizontal outflow face was given below.

$$[\frac{\alpha KY}{|Q|}]^2 - \frac{\alpha KX}{|Q|} - 1 = 0 \qquad 2.3$$

$$Y_o = \frac{|Q|}{\alpha K} \qquad 2.4$$

$$X_o = \frac{|Q|}{2\alpha K} \qquad 2.5$$

Where Y is the depth of the interface below mean sea level, α is the excess density ratio, Y_o and X_o are the co-ordinates of the interface, X is the distance from the coast to the interface Q is the fresh water discharge and K is the effective coefficient of permeability. The depth of interface at the outflow face Y_0 for a confined aquifer with a vertical outflow face was obtained as $\frac{0.741|Q|}{\alpha K}$ and for confined aquifer as $\frac{0.722|Q|}{\alpha K}$

Rumer and Harleman (1963) derived an approximate equation for the velocity of movement of the sea water wedge into a fresh water aquifer when it was suddenly exposed to the sea water.

$$V_T = (\alpha KD/4\,nt)^{1/2} \tag{2.6}$$

Where V_T is the velocity of the wedge toe at time 't', α is the excess density ratio K is the effective coefficient of permeability and n is the porosity. This equation was not generally used because a case of sudden exposure of an aquifer to sea water was not often met with in nature.

They derived an equation for the interface in a confined aquifer with a vertical outflow face with Dupuit's approximation.

$$Y = \left[\frac{2|Q|}{\alpha K}X + 0.55\left(\frac{|Q|}{\alpha K}\right)^2\right]^{1/2} \tag{2.7}$$

Where Y is the depth of the interface from the mean sea level, Q is the fresh water discharge α is the excess density ratio, x is the distance from coast to interface and K is the effective coefficient of permeability.

Charmonman (1965) used a new approach to arrive an exact equation valid for unconfined aquifers. He observed the behaviour of the flow boundaries and stream lines in the complex potential plane and used some approximations to arrive at an equation for the interface in an unconfined aquifer with a horizontal outflow face.

$$X = (1 + \alpha) \frac{\alpha K}{2|Q|} Y^2 - \frac{(1 - \alpha)}{2} \frac{|\phi|}{\alpha K} \qquad 2.8$$

Where X is the length of the intrusion α is the excess density ratio, K is the effective coefficient of permeability, Y is the depth of the interface and Q is the fresh water discharge. He assumed a free surface and neglected the seepage face above mean sea level.

He proceeded to compare the solution with that for confined aquifers. He arrived at the conclusion that the error in the interface profile by approximating an unconfined flow case to that of a confined one was about 2.6 per cent at the shore line and 1.3 per cent at infinite distance from the shore line.

Columbus (1965) developed an equation for the length of intrusion, considering steady recharge into the unconfined aquifer.

$$L = \frac{(1 + \alpha)\,\alpha K D^2}{2\,Q_T} - \frac{0.741^2\,(Q_T + WL)^2}{2\,Q_T\,\alpha K\,(1 + \alpha)} \qquad 2.9$$

Where L is the length of intrusion, is the excess density ratio, K is the effective coefficient of permeability, D is the depth of the aquifer below mean sea level. Q_T is the unit discharge entering the aquifer at the toe of the intruded wedge and w is the rate of discharge per unit area from the ground level supplied for the entire length from the coast line.

When W = 0, equation becomes

$$L = \frac{(1+\alpha)\,\alpha K D^2}{2\,Q_T} - \frac{0.741^2}{2(1+\alpha)} \quad \frac{Q_T}{\alpha K} \qquad 2.10$$

He investigated the problem experimentally with a viscous flow analog model using salt water and distilled water. His experiments showed that the equation for the length of intrusion generally fits well with experimental results except near the outflow face.

Ippen (1966) conducted the salinity intrusion experiments in tidal flume of the water ways experiment station in Viksburg, Mississippi. Basic factors governing the salinity distribution in estuaries were the effect of the tide throughout the salinity intrusion length, the effect of gravitational forces due to density variations between fresh water from upland sources and saline water entering from the sea, and the gravitational forces needed to produce a net seaward transport of fresh water. The result was a complete description of the distribution of mean local salinity throughout the estuary of uniform section and for which the tidal conditions in the estuary, ocean salinity and fresh water flow were known in addition to the geometry and roughness of the channel.

Vappicha (1975) had done experimental and analytical investigations on the characteristics of steady and transient interfaces. The experimental results established the validity of the hypothesis employed in developing the solution. An explicit equation was derived for the steady interface profile in an unconfined aquifer with a vertical outflow face. Equation for the interface was given by

$$X = (1 + \alpha) \left[\frac{KY^2}{2\,Q} - \frac{0.26\,Q}{\alpha\,K}\right] \qquad 2.11$$

Where X is the length of intrusion, α is the excess density ratio, Y is the depth of the aquifer, K is the coefficient of permeability and Q is the fresh water discharge.

He concluded that for determining the length of intrusion in a finite depth aquifer, the equation of the interface profile could be used the depth of interface at coastal front for an unconfined aquifer with a vertical outflow face was $0.722\,|Q|/\alpha K$. The steady state solution obtained for the interface profile was not only useful in locating the interface but also for formulating the initial conditions for analysing transient interface problems.

Rodda et al. (1976) reported that the encroachment of salt water could limited by discharging the fresh ground water into the sea. They mentioned that when ground water was moving a dynamic rather than an hydrostatic equilibrium exist between fresh and salt water and the depth to the interface was greater than that forecast by the Ghyben-Herzberg equation. The interface between fresh and salt water was marked by a zone of diffusion and the width of the zone diffusion was related to the porosity.

Vappicha and Nagaraja (1976) developed an approximate solution for the transient interface in a coastal aquifer. Adopting the principle of quasi-steady state analysis, the basic equation was formulated as an ordinary differential equation of first order. The equation was solved analytically and numerically for three different boundary conditions. The solution was compared with experimental results from a viscous flow analog model. The basic equation was given as

$$\frac{dy_o}{dt} = - \frac{Q_T + \alpha K Y_o / \beta}{\frac{(1+\alpha)\beta n}{6}\left[\frac{D^3}{Y_o^2} + 3D - 4Y_o\right]} \qquad 2.12$$

This was an ordinary differential equation defining the variation of Y_o with respect to time. Where Y_o is the Y co-ordinate of the interface. Q_T is the fresh water discharge at wedge toe and $\beta = 0.722$.

This equation was derived for the following three boundary conditions.

A. Linear variation of surface source level

$$Q_T = \eta K \left[\frac{h_u^2 - (1+\alpha)^2 D^2}{2(L_a - L)}\right] \qquad 2.13$$

Where Q_T is the discharge at the wedge toe K is the coefficient of permeability, h_u is the elevation of surface source level, α is the excess density ratio, D is the depth of aquifer below mean sea level, L_a is the aquifer length L is the length of sea water wedge and η is the ratio of the actual fresh water discharge to the discharge obtained from Dupuit's equation.

B. Linear variation of fresh water discharge at wedge toe

The fresh water discharge was varied linearly at the wedge toe from Q_I to Q_{ff} in time T_c.

$$Q_T = Q_I + \frac{Q_{ff} - Q_I}{T_c}\, t \qquad 2.14$$

Where Q_T is the discharge at the wedge toe Q_I is the initial fresh water discharge, Q_{ff} is the final fresh water discharge, T_c is the time required to effect the change in surface source level and t is the time variable.

C. Sudden variation of fresh water discharge at wedge toe.

$$\frac{dY_o}{dt} = \frac{-Q_{ff} + \alpha KY_o/\beta}{\frac{(1+\alpha)\beta n}{6} \left[\frac{D^3}{Y_o^2} + 3D - 4Y_o \right]} \qquad 2.15$$

Where $Q_T = Q_{ff}$

This equation was solved by exact and linearised solution.

Exact solution was given as

$$t = \frac{-C}{A}[1/Y_o - 1/Y_{oI} - \frac{B}{A} \ln Y_o/Y_{oI}] - \frac{G}{A}[Y_o - Y_{oI}] -$$

$$- [\frac{BC}{A^2} + \frac{E}{B} - \frac{AG}{B^2}] \ln A + BY_o/ A + BY_{oI} \qquad 2.16$$

where t is the time

$A = \dfrac{6\,Q_{ff}}{(1+\alpha)\ \beta n}$

$B = \dfrac{6\,\alpha K}{(1+\alpha)\ \beta^2 n}$

$C = D^3$

$E = 3D$

$G = -4$

Linearised solution was given as

$$Y_o = Y_{of} + \frac{Y_{oi} - Y_{of}}{e^{\frac{\alpha K t}{A_1 \beta}}} \qquad 2.17$$

$$\text{Where } A_1 = \frac{(1+\alpha)\beta n}{6}\left[\frac{D^3 + 3D}{Y_{oa}^2} - 4Y_{oa}\right]$$

Y_o is the depth of interface at outflow face. Y_{oi} is the initial value of Y_o, Y_{of} is the final value of Y_o and Y_{oa} is the average value of Y_{oi} and Y_{of}.

The quasi-steady state analysis employed for predicting the interface movement under various boundary conditions gave a simple procedure to arrive at approximate solutions for the transient interface problem either in the advancing or retreating conditions.

Bouwer (1978) reported that saltwater could move upward into the fresh ground water in aquifers underlain by saline water. The pumping of water from the wells caused the fresh water salt water interface to rise below the well. This uponing was in response to the pressure reduction on the interface due to drawdown of the water table around the well. If the bottom of the well was close to the saline water and the discharge was relatively high, then the discharge could be a mixture of fresh and saline ground water.

Daniel et al. (1978) worked on subsurface seawater intrusion barrier analysis. They constructed an experimental subsurface barrier in a small buried valley on Miyako-jima Island, Japan. The purpose was to increase the usable storage of ground water within the aquifer, and thus improving the availability of water for irrigation. Modification of pumping pattern and artificial recharge were employed to avoid the sea water intrusion. They reported that the problem of sea water intrusion in an unconfined coastal aquifer caused by ground water withdrawal in the dry season. They analysed numerically using the Darcy equation and the Dupuit approximations. Simulations were carried out for conditions of ground water flow both before and after the construction of a proposed semipervious subsurface barrier. The analysis lead to a conclusion that the semipervious barrier was able to delay sea water intrusion even under the extreme condition of total drought and continuous pumping.

Raghunath (1982) gave an equation for total length of intrusion and time required for the foe of wedge to move the length.

$$L = \frac{K' H^2}{2q} \qquad 2.18$$

Where $K' = K \frac{\gamma_s - \gamma_f}{\gamma_f}$

L is the total length of intrusion, H is the thickness of the aquifer, q is seaward fresh water flow per unit width of ocean front, K is the permeability of the aquifer, γ_f is the specific weight of fresh water and γ_s is the specific weight of sea water.

$$t = \frac{\tilde{t}nK'H^3}{q_{ul}^2} \qquad 2.19$$

Where t is the time required for the toe of the wedge to move, n is the porosity $\tilde{t}$ is dimensionless factor to be obtained from a master curve and q_{ul} is the ultimate fresh water flow per unit width.

He had given a detailed study of advancement of saltwater wedge with increased ground water exploitation. He also computed the position and shape of the interface for various cases. He concluded that the rate of landward sea water intrusion was useful for planning ground water exploitation in coastal area.

Basak and Sabu Abraham (1983) had done a study on salinity intrusion problems in coastal wells of Trivandrum district. This study revealed a definit relation between depth of water table and salinity. Lowering of ground water table was associated with the increase in salinity. Field observations indicated that depending on the locations within the coastal belt, every centimeter drop of ground water table was met with an increase of 5 to 44 ppm of total dissolved solids and an increase of 2 to 19 ppm chlorides. The sea water was directly responsible for increase of salinity and it was affected by a distance of a half a kilometer from the shore.

Institute of Hydraulics and Hudrology Poondi conducted a study on saltwater intrusion on coastal aquifers of Tamil Nadu (1984). They started ground water investigations in three aquifers namely Tamaracipakkan, Punjetty and Minjur. The analysis of the water quality data indicated that wells in Minjur aquifer were showing signs of serious changes in water quality especially increase in the chloride concentrations. The analysis of data on geophysical survey conducted in the Minjur aquifer showed that the fresh saltwater interface exist at about 4 km west from the coast of Bay of Bengal during 1969. Based on the latest survey, the present sea fresh water interface line was demarcated with a westward movement of about 4 to 6 km from 1969 interface line. They concluded that there was definite salt water intrusion in the Minjur coastal aquifer.

Rajagopalan et al. (1986) conducted a study on saltwater intrusion in coastal Kerala - A case study in Kozhikode district. The results indicated that the increase in salinility during the critical period was mainly due to the wells tapping from the mixing zone of fresh and salt water above the interface.

Dave et al. (1987) had done a study on salinity ingress along the coastal areas of Saurashtra - Problems and remedial measures. Their results suggested that the excessive withdrawal of ground water without corresponding provision of adequate recharge lowered the water table gradually to a considerable extent and this resulted in saline water intrusion due to a reversed hydraulic gradient. They suggested that the artificial recharge techniques, salinity control techniques and management techniques were the remedial measures for salinity ingress along the Saurashtra region.

Gajendragad et al. (1987) conducted a study on sea water ingression into Pavanji river leading to subsurface water contamination. The aim of their study was to determine the effects of salt water intrusion and to understand problems related thereto. The mitigative measures of sea water ingression into the rivers were the construction of salt exclusion dam and percolation tanks.

Elango, Manickam and Sakthivadivel (1987) conducted a study on saline ground water in heavily exploited coastal aquifers - A case study in Madras. This study was carried out to understand the extent and sources of salinity. They concluded that the high salinity may be attributed due to mixing of saline water by intrusion of sea water and by infiltration of saline back water in rivers, irrigation returns flow which was enriched in concentration due to evaporation and percolation of rain water through salt pans in eastern part of the area.

Molykutty (1987) had done a study on salinity intrusion problems in coastal tracts of Trivandrum district namely Meenamkulam, Puthukkurichi and Perumathura. The main purpose of the study was to check whether there is salt water intrusion problems in the present condition. She estimated the maximum rate of exploitation from the aquifer in three villages to avoid the possibility of intrusion. A computer programme was developed from quasi-steady state analysis to find the variation of the ordinate and length of intrusion with respect to time. The length of intrusion was also calculated by Ghyben-Herzberg formula.

It was found that sufficient quantity of ground water was available in the coastal tracts of Trivandrum district. The available groundwater in the island portion of Perumathura was completely polluted by high salinity content. But at the time of observation there was no problem of salinity intrusion in Meenamkulam and Puthukkurichi.

Jacob and Raman (1987) used surface geophysical methods for mapping fresh-salt water interfaces in the coastal tracts. The electrical resistivity and VLF techniques were used for mapping the fresh and salt water interfaces. Vertical electrical sounding (VES) was conducted at selected stations across the coast line. While VLF resistivity measurements were observed as a rapid tool. Their studies shown that the technique was highly sensitive to detect saline fresh water boundary. Based on this study, the main source of potable water in some of the coastal tracts had been prepared from the map.

Swamy (1987) conducted a study on analysis of interface of sea water intrusion into coastal aquifers. He presented an analytical model and that was based on two dimensional flow with a free surface.

He developed an equation for length of intrusion.

$$L = \frac{KH^2 \alpha(1 + \alpha)}{2q} \qquad 2.20$$

Where L is the length of intrusion, K is the permeability of the medium of aquifer, H is the maximum depth of interface below water table, α is the excess density ratio and q is the volumetic flow rate per unit volume of the medium.

He also studied on characteristics of interface on recharge in sea water intrusion. He reported that the theory and equations derived for the interface between the inland fresh water and saline sea water. He suggested two methods for artificial recharge operations. One of the most common method was the utilization of holding basins and the second one was the modified stream bed.

Materials and Methods

MATERIALS AND METHODS

3.1 The sites

Field observations were taken from the selected sites of three villages namely Nattika, Talikulam and Edamuttam in Trichur District as explained in the following paragraphs. The bore hole data for these sites were obtained from the office of the State Ground Water Department.

3.1.1. Nattika

The site was located 1 km north of Nattika junction. The wells were located in the private land owned by Smt. Ammukutti Aruketti. Location of the site is shown in Fig. 3.1. Figure 3.2 gives the position of the wells with respect to the coast. Depth of the aquifer was obtained from the bore hole data. The lithology of the aquifer is given in Appendix I. For calculating the aquifer discharge, the height of water table was obtained by taking the levels. The water samples were collected from the wells to test the salinity of water.

3.1.2 Talikulam

The site was near to the Nambikadavu junction. The position of the wells were in a plot possessed by Smt. Alli Furaden, Sri Bukhari Aravasniyil and Sri Ahmed Kunju, Puthrappayil. Location of the site is shown in Fig. 3.3. Figure 3.4 shows the position of the wells. The lithological data are given in Appendix II. The height of the water table was measured

FIG. 3·1. NATTIKA SITE. (LOCATION OF SITE IN THE VILLAGE MAP.)

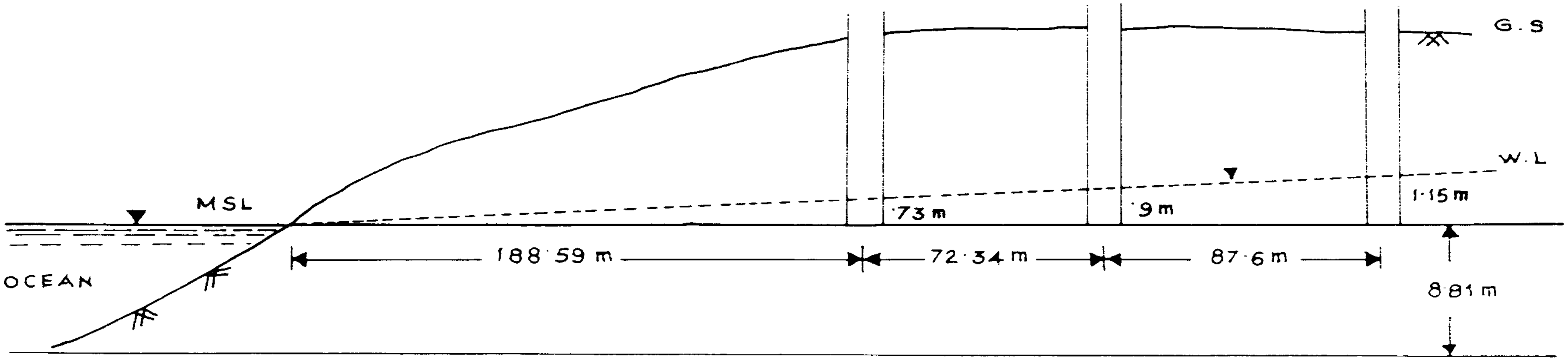


FIG 3·2 LOCATION OF WELLS.
SITE - NATTIKA.

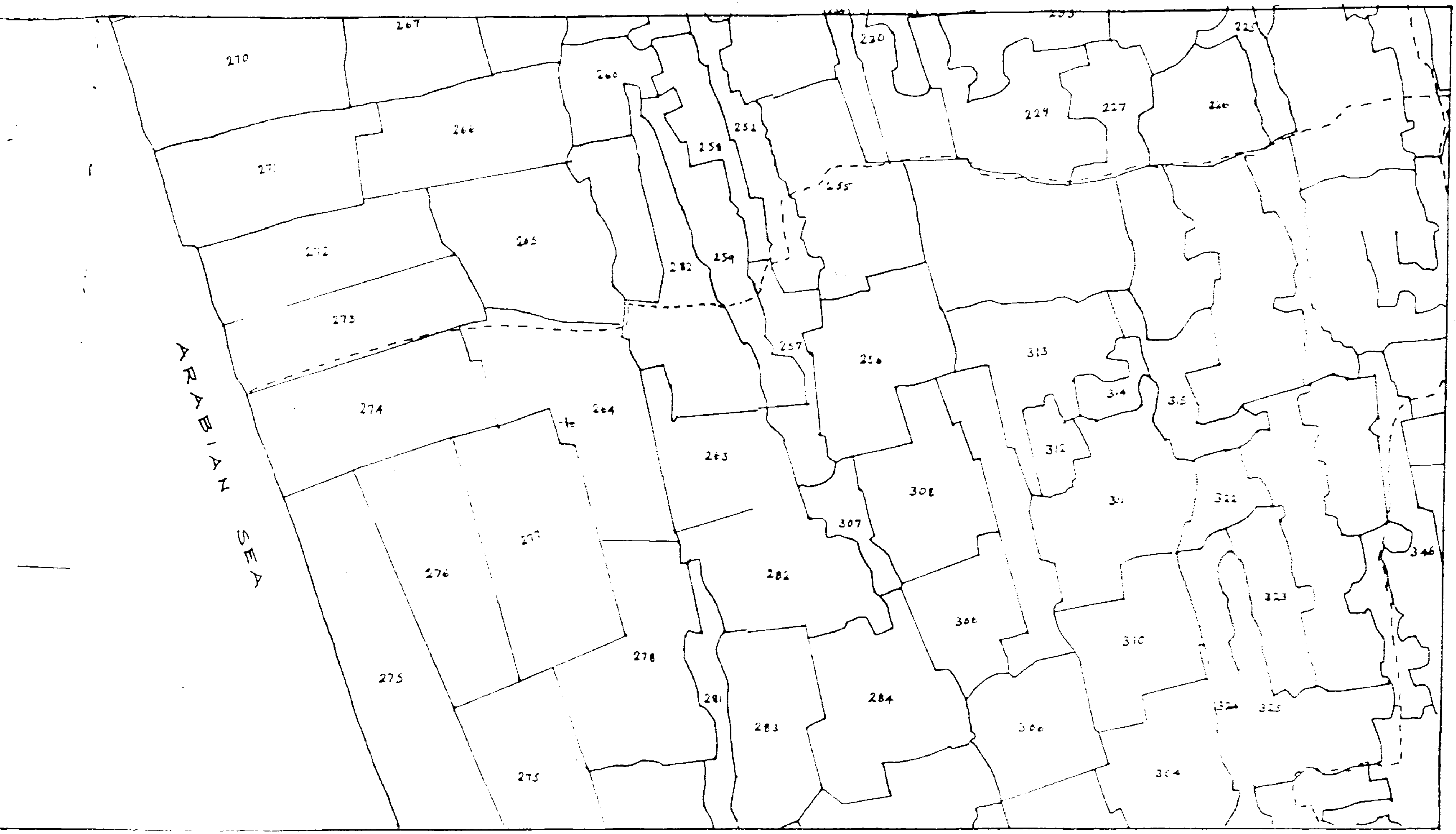


FIG 3·3 TALIKULAM SITE (LOCATION OF SITE IN THE VILLAGE MAP).

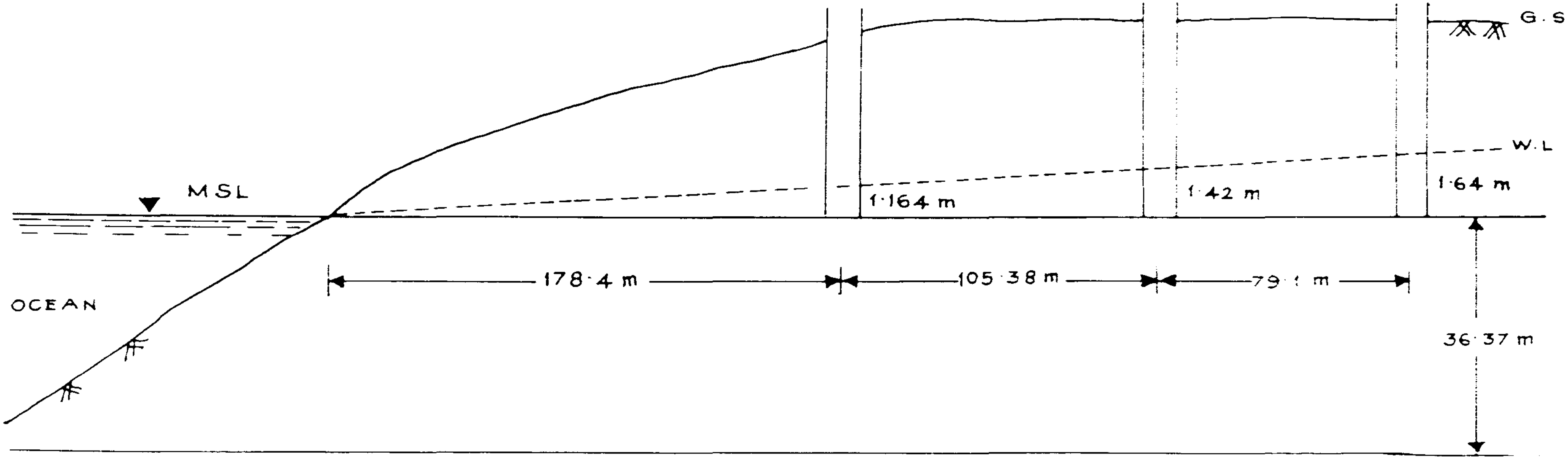


FIG.3·4. LOCATION OF WELLS

SITE - TALIKULAM

to calculate the aquifer discharge. For analysing the quality of water, the water samples were collected from each wells.

3.1.3 Kazhimbram

This site was in Edamuttam village and was located 500 m north to Edamuttom High School junction. The wells were situated in the land of Smt. Sushama, Sri Kuttan Naduerippil and Sri Sukumaran Neduerippil. Figure 3.5 shows the location of the site. Appendix III gives the lithological data of the aquifer. The height of the fresh water was measured from each wells by taking the levels. The water samples from each wells were collected to test the quality of water.

3.2 Aquifer parameters

With reference to the bore hole data, the aquifer was found to be unconfined in nature. The bottom of it was assumed to be horizontal. The various parameters are discussed below. The values are given in the Chapter IV.

3.2.1 Coefficient of permeability (K)

The coefficient of permeability is the rate of flow per unit cross sectional area under unit hydraulic gradient. The standard values of coefficient of permeabilities for different types of soils are given in Appendix IV. From these, the values of K for different layers were assessed using the lithological data. Lithology of various sites are given in Appendix I, II & III.

FIG. 3.5. KAZHIMBRAM SITE (LOCATION OF SITE IN THE VILLAGE MAP.)

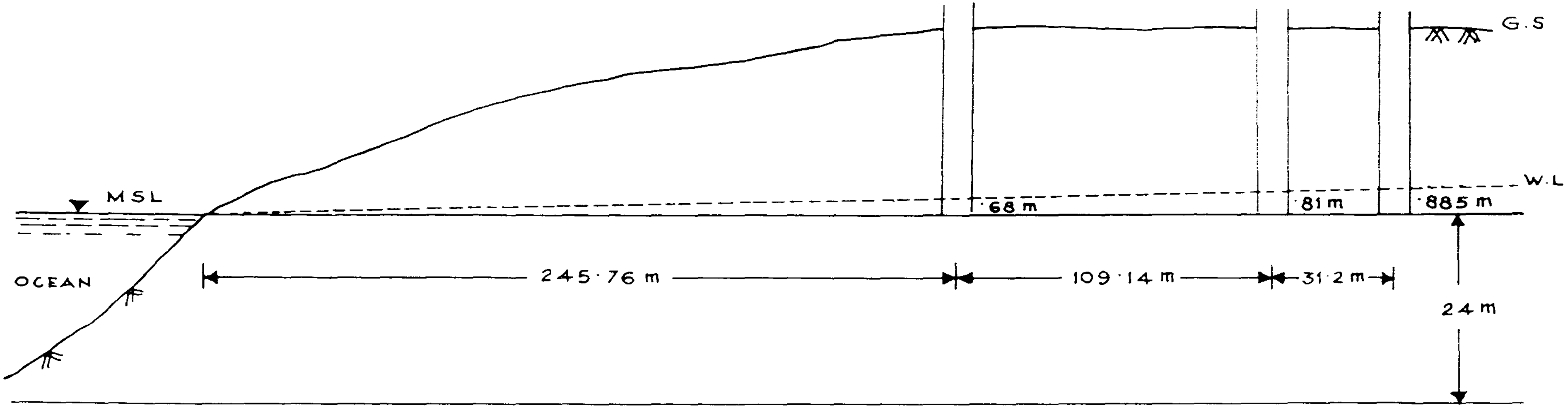


FIG.3·6 LOCATION OF WELLS.

SITE - KAZHIBRAM

The effective coefficient of permeability of the aquifer was found out by using the formula

$$K = (K_1Z_1 + K_2Z_2 + \dots\dots)/(Z_1 + Z_2 + \dots\dots) \qquad 3.1$$

where K is the effective coefficient of permeability of the aquifer. K_1, K_2 .... are the coefficient the permeability of each layer. Z_1, Z_2 ... are the thickness of each layer obtained from the lithology.

3.2.2 Fresh water discharge from the aquifer (Ql)

For calculating the aquifer discharge two existing wells were located in such a way that the line joining between them was perpendicular to the coast line. The seaward discharge was calculated using the formula

$$Ql = \frac{K}{2X}(h_1^2 - h_2^2) \qquad 3.2$$

where K is the coefficient of permeability of the aquifer, X is the distance between wells. h_1 and h_2 are the height of water levels from the impermeable stratum.

3.2.3 Porosity (n)

Porosity is an index of relative volume of pores. It is influenced by the textural and structural characteristics of the soil. Porosity of different soils are given in Appendix V. The porosity of medium to coarse sand was taken as 0.4.

3.2.4 Excess density ratio (α)

Density of fresh water (γf) was taken as 1.0 g/cm^2 and the density of sea water (γs) was taken as 1.025 g/cm^2. The excess density ratio was calculated as 0.025. By the following equation $= (\frac{\gamma s - \gamma f}{\gamma f})$ 3.3

3.2.5 Depth of the aquifer (D)

Depth of the aquifer was taken from the bore hole data. It is the level difference between the mean sea level and the impermeable strata.

3.3 Steady interface in an unconfined aquifer with a vertical outflow face

Under natural conditions the slope of the water table was towards the sea through an aquifer and a fresh water - sea water interface was established in the aquifer below mean sea level. The problem under study was schematised in Fig. 3.7. AB is the free surface and CD is the sea water fresh water interface. The outlfow face AC has two parts; Y_o below mean sea level and S_o above mean sea level. According to the Ghyben - Herzberg principle, the value of S_o was taken as αY_o. When the free surface and the interface were extended beyond the coast line they necessarily met at 0' on the mean sea level as in Fig. 3.7. The point 0' was taken as the origin of co-ordinates for the study.

3.3.1 Assumptions

1. The aquifer was homogenous and isotropic.
2. Steady incompressible two dimensional flow conditions exist in the aquifer

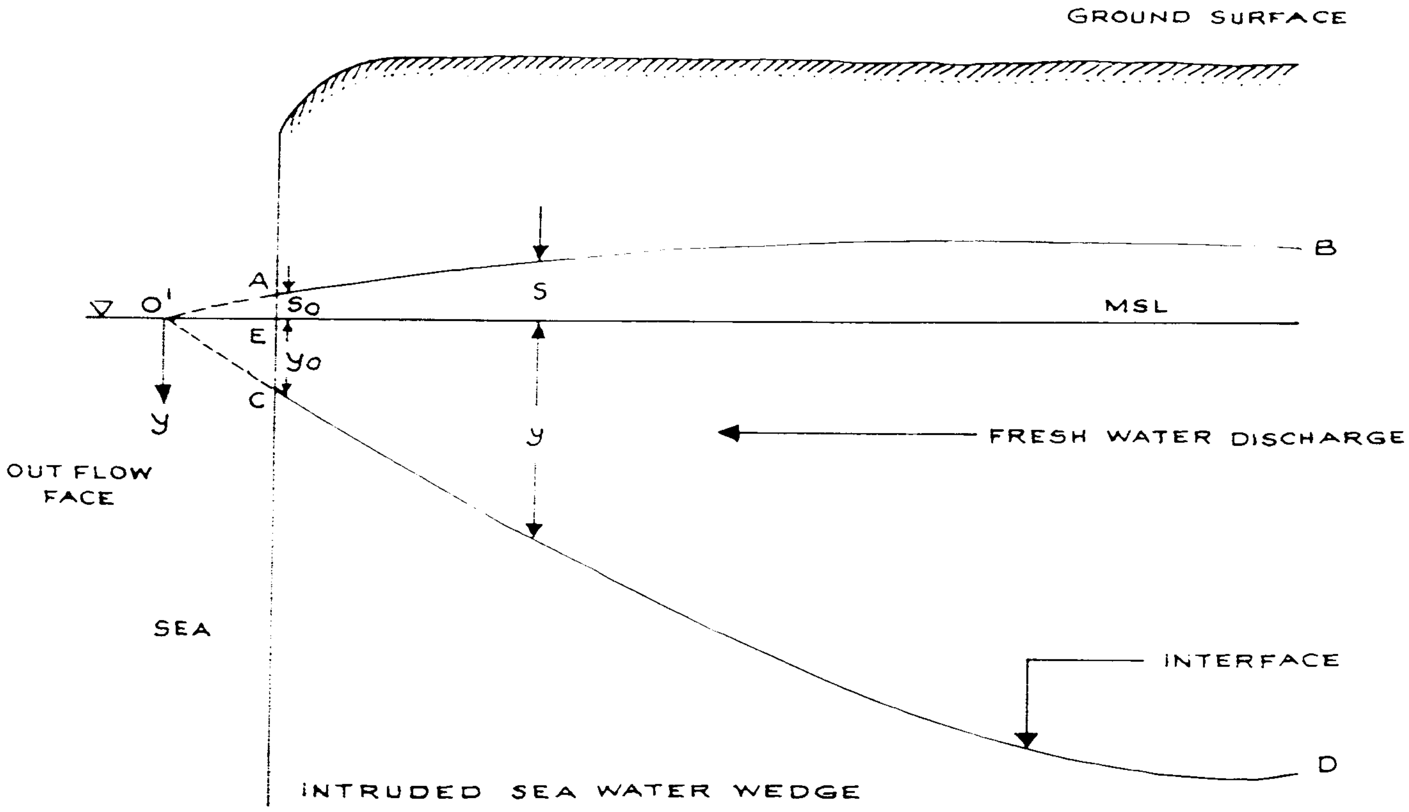


FIG.3·7 DEFINITION SKETCH.

3. Hydrodynamic dispersion was negligible and the interface could be treated as a sharp one.

4. The depth and length of the aquifer were large, so that the presence of impermeable boundaries would not affect the flow in the fresh water region.

3.3.2 Basic equations

In general, steady ground water flow is governed by Laplace equation.

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad 3.4$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = 0 \qquad 3.5$$

where ϕ and ψ are the potential and stream functions respectively.

The complex potential function $W = \phi + i\psi$ will be analytic in the flow domain as both ϕ and ψ satisfy the Laplace equation. When $Z = x + iy$ the physical co-ordinates x and y also satisfy the Laplace equation in ϕ and ψ

i.e. $Z = F(W)$

$$x + iy = F(\phi + i\psi) \qquad 3.6$$

Differentiating with respect to ϕ and ψ twice separately

$$\frac{\partial x}{\partial \phi} + \frac{i\,\partial y}{\partial \phi} = \frac{dF}{dW} \qquad 3.7$$

$$\frac{\partial^{2}}{\partial \phi 2} + \frac{i\,\partial^{2}}{\partial \phi 2} = \frac{d^{2}F}{dW^{2}} \qquad 3.8$$

similarly

$$\frac{\partial x}{\partial \psi} + \frac{i\,\partial y}{\partial \psi} = \frac{i dF}{dW} \qquad 3.9$$

$$\frac{\partial^{2}x}{\partial \psi^{2}} + \frac{i\,\partial^{2}y}{\partial \psi^{2}} = \frac{i d^{2}F}{dW^{2}} \qquad 3.10$$

Multiplying 3.9 by i

$$\frac{i\,\partial x}{\partial \psi} - \frac{\partial y}{\partial \psi} = \frac{-dF}{dW} \qquad 3.11$$

adding 3.7 and 3.11

$$\left(\frac{\partial x}{\partial \phi} - \frac{\partial y}{\partial \psi}\right) + i\left(\frac{\partial x}{\partial \psi} + \frac{\partial y}{\partial \phi}\right) = 0 \qquad 3.12$$

equating real and imaginary

$$\frac{\partial x}{\partial \phi} - \frac{\partial y}{\partial \psi} = 0 \qquad 3.13$$

therefore
$$\frac{\partial x}{\partial \phi} = \frac{\partial y}{\partial \psi} \tag{3.14}$$

and
$$\frac{\partial x}{\partial \psi} + \frac{\partial xy}{\partial \phi} = 0 \tag{3.15}$$

adding 3.8 and 3.10

$$\frac{\partial^2 x}{\partial \phi^2} + \frac{\partial^2 x}{\partial \psi^2} + i\left(\frac{\partial^2 y}{\partial \phi^2} + \frac{\partial^2 y}{\partial \psi^2}\right) = 0 \tag{3.16}$$

therefore
$$\frac{\partial^2 x}{\partial \phi^2} + \frac{\partial^2 x}{\partial \psi^2} = 0 \tag{3.17}$$

and
$$\frac{\partial^2 y}{\partial \phi^2} + \frac{\partial^2 y}{\partial \psi^2} = 0 \tag{3.18}$$

where $\phi = -Kh$

$h = \frac{P}{\gamma} - y$

where h is the piezometric head, K is the coefficient of permeability, P is the pressure at the point and γ is the specific weight of water.

3.3.3 Boundary conditions

1. Along the free surface, the pressure was atmospheric which was taken as zero. With mean sea level as datum and Y measured downwards,

$h = -Y$ or $\phi = KY$

2. Along the interface, the pressure on the fresh water side (p_f) was same as the pressure on the sea water side (p_s)

i.e. $p_f = p_s = \gamma_s y$

$$h_f = (\frac{p}{\gamma_f}) - y$$

$$= (\frac{\gamma_s y}{\gamma_f}) - y = (\frac{\gamma_s - \gamma_f)y}{\gamma_f}$$

$$= \alpha y$$

$$\phi = -Kh_f = -\alpha Ky$$

3. Both free surface and interface were stream lines. Their corresponding stream functions had values 0 and Q respectively.

For free surface $\varphi = 0$

For interface $\varphi = -Q$

4. The depth of interface at the outflow face Y_o for a confined aquifer with a vertical outflow face was obtained by Henry as equal to $\frac{0.741\,|Q|}{\alpha K}$. Where Q is the fresh water discharge per metre width. The error in Y_o in extending this result to an unconfined case was given by Charmonman and others as about 2.6 per cent. Combining these two findings, for an unconfined aquifer with a vertical outflow face.

$$Y_o = \frac{0.722\,|Q|}{\alpha K} \qquad 3.19$$

Q is negative as fresh water discharge takes place in a direction opposite to X. The constants 0.741 and 0.722 were called aquifer constants for confined and unconfined aquifers respectively.

3.3.4 The solution

The basic equations and boundary conditions were non dimensionalised to obtain a solution independent of dimensions in the physical plane by the following substitutions.

$$\bar{X} - \frac{\alpha K X}{|Q|}, \quad \bar{Y} = \frac{\alpha K Y}{|Q|} \qquad 3.20$$

$$\bar{\phi} = \frac{\phi}{|Q|}, \qquad \bar{\psi} = \frac{\psi}{|Q|} \qquad 3.21$$

where Q is the fresh water discharge.

The dimensionless boundary conditions for the free surface become

$$\phi = \frac{\bar{Y}}{\alpha} \qquad \psi = 0 \qquad 3.22$$

and for the interface

$$\phi = -Y, \quad \psi = -1 \qquad 3.23$$

Therefore $\bar{X}$ and $\bar{Y}$ also satisfied the Laplace equation in ϕ and ψ

i.e. $$\frac{\partial^2 \bar{X}}{\partial \phi^2} + \frac{\partial^2 \bar{X}}{\partial \psi^2} = 0 \qquad 3.24$$

$$\frac{\partial^2 \bar{Y}}{\partial \bar{\phi}^2} + \frac{\partial^2 \bar{Y}}{\partial \bar{\psi}^2} = 0 \qquad 3.25$$

Therefore the flow domain in the physical plane could be mapped on the complex potential plane as shown in Fig. 3.8. As x increases inland of the aquifer the free surface will flatten out. Hence the streamlines will tend to become parallel and uniform.

At a large distance from the coast line $\bar{y}$ varied linearly with $\bar{\psi}$

$$\bar{y} = c_1 \bar{\psi} + c_2 \qquad 3.26$$

where c_1 and c_2 are constants

On the free surface $\bar{\psi} = 0$, $\bar{y} = \alpha \bar{\phi}$

Therefore $c_2 = \alpha \bar{\phi}$

Substituting for c_2 in equation 3.26

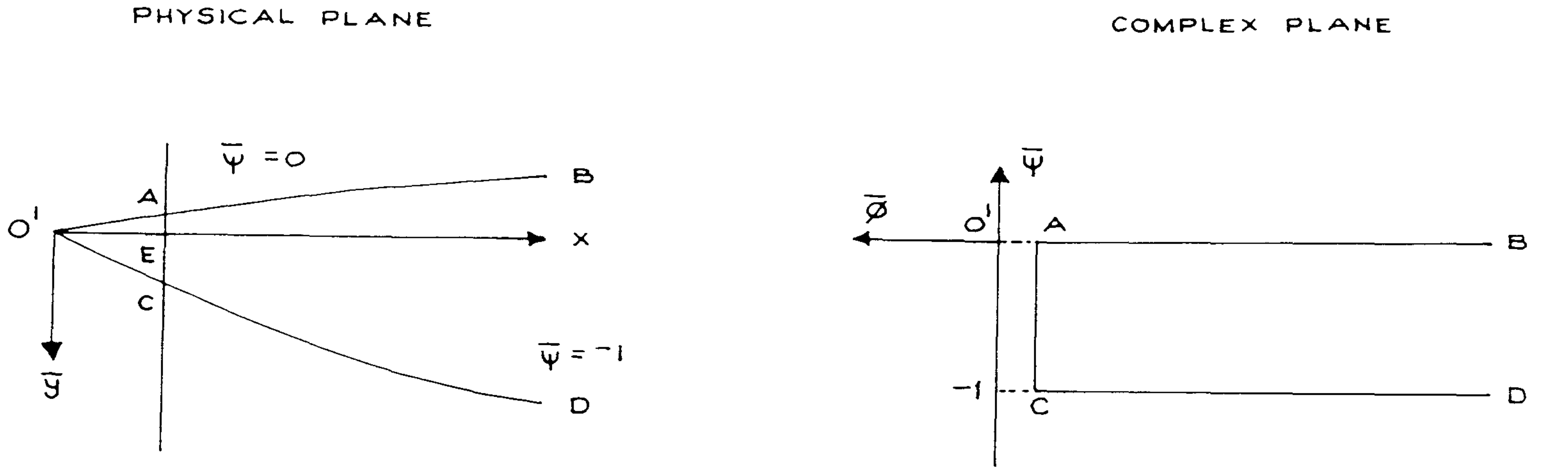
$$\bar{y} = c_1 \bar{\psi} + \alpha \bar{\phi} \qquad 3.27$$

On the interface $\psi = -1$, $\bar{y} = -\bar{\phi}$

Therefore $c_1 = \alpha \bar{\phi} + \bar{\phi} = \bar{\phi} (\alpha + 1)$

Substituting c_1 in equation 3.27 $\bar{y} = \bar{\phi}(1+\alpha) \bar{\psi} + \alpha\bar{\phi}$ 3.28

$$= (1 + \alpha) \bar{\phi} \bar{\psi} + \alpha \bar{\phi}$$



$$\bar{x} = \alpha K x / |Q|$$

$$\bar{y} = \alpha K x / |Q|$$

$$\bar{\phi} = \phi / |Q|$$

$$\bar{\Psi} = \Psi / |Q|$$

FIG.3·8. PLOT BOUNDARIES.

Differentiating equation 3.28 with respect to $\bar{\phi}$,

$$\frac{\partial \bar{Y}}{\partial \psi} = (1+\alpha)\psi + \alpha$$

From Cauchy - Riemann equation,

$$\frac{\partial \bar{Y}}{\partial \phi} = -\frac{\partial \bar{X}}{\partial \psi}$$

$$\therefore \quad \frac{\partial \bar{X}}{\partial \phi} = -[(1+\alpha)\psi + \alpha] \qquad 3.29$$

Differentiating equation 3.28 with respect to ψ,

$$\frac{\partial \bar{Y}}{\partial \bar{\psi}} = (1+\alpha)\phi$$

Again using Cauchy Riemann equation,

$$\frac{\partial \bar{Y}}{\partial \psi} = \frac{\partial \bar{X}}{\partial \phi}$$

$$\frac{\partial \bar{X}}{\partial \phi} = (1+\alpha)\phi \qquad 3.30$$

We know,

$$d\bar{X} = \left(\frac{\partial \bar{X}}{\partial \psi}\right) d\psi + \left(\frac{\partial \bar{X}}{\partial \phi}\right) d\phi \qquad 3.31$$

Substituting values of $\frac{\partial \bar{X}}{\partial \psi}$ and $\frac{\partial \bar{X}}{\partial \phi}$ in equation 3.31

The equation was obtained as

$$d\bar{X} = [-(1+\alpha)\psi - \alpha]\, d\phi + [(1+\alpha)\phi]\, d\bar{\phi}$$

Integrating

$$\bar{X} = (1+\alpha)\frac{\bar{\psi}^2}{2} - \alpha\bar{\psi} + (1+\alpha)\frac{\bar{\phi}^2}{2} + C$$

Where C is the constant of integration

$$\bar{X} = \frac{(1+\alpha)}{2}[\bar{\phi}^2 - \bar{\psi}^2] - \alpha\bar{\psi} + C \qquad 3.32$$

This was valid for the entire domain of fresh water region.

Equation to the free surface

$$\bar{\phi} = \bar{Y}/\alpha, \quad \bar{\psi} = 0$$

$$\text{Therefore } \bar{X} = \frac{(1+\alpha)}{2}[\frac{\bar{Y}^2}{\alpha^2} + 0] - 0 + C$$

$$= \frac{(1+\alpha)}{2} \times [\frac{\bar{Y}}{\alpha}]^2 + C \qquad 3.33$$

Free surface passing through the origin,

$\bar{X} = 0;\ \bar{Y} = 0;\ C = 0$

$$\bar{X} = \frac{(1+\alpha)}{2}[\frac{\bar{Y}}{\alpha}]^2 \qquad 3.34$$

Equation to the interface

$$\bar{\phi} = -\bar{Y} \quad \psi = \bar{1}$$

$$\bar{X} = \frac{(1+\alpha)}{2}[(\bar{Y}^2 - 1)] + \alpha + C \qquad 3.35$$

Interface passing through the origin $\bar{X} = 0$; $\bar{Y} = 0$

Substituting the values of $\bar{X}$ and $\bar{Y}$ in equation in 3.35

$$C = \frac{(1 - \alpha)}{2} \qquad 3.36$$

Substituting the value of C in equation 3.35

$$\bar{X} = \frac{(1 + \alpha)}{2}(\bar{Y}^2 - 1) + \alpha + \frac{(1 - \alpha)}{2} \qquad 3.37$$

$$\bar{X} = \frac{(1 + \alpha)}{2}\,\bar{Y}^2 \qquad 3.38$$

Using the equation 3.19 $\quad Y_o = \frac{0.722\,|Q|}{\alpha K}$

Non dimensionalising we get $\bar{Y}_o = \frac{\alpha K Y_o}{|Q|}$

$$= \frac{\alpha K}{|Q|} \cdot \frac{0.722 Q}{\alpha K} = 0.722$$

Therefore at the coast line the equation to the free surface,

$$\bar{X} = \bar{X}_o = \frac{(1 + \alpha) Y_o^2}{2} = 0.26\,(1 + \alpha)$$

3.3.5 Position of origin

The origin of co-ordinates O' was a hypothetical point. To plot the stream lines, the origin was shifted to 0 from which the distances could be directly measured. 0 was the junction of the vertical outflow face with the mean sea level.

Accordingly the equation of the free surface becomes

$$\hat{X} = \frac{(1+\alpha)}{2} (\hat{Y}/\alpha)^2 - 0.26(1+\alpha) \qquad 3.38$$

and for the interface

$$\hat{X} = \frac{(1+\alpha)}{2} \hat{Y}^2 - 0.26(1+\alpha) \qquad 3.39$$

$$\hat{X} = \frac{\alpha K X}{|Q|}, \quad X = \frac{\hat{X}|Q|}{\alpha K}$$

Substituting the value of $\hat{X}$ and $\hat{Y}$ in equation 3.38 and equation 3.39.

For free surface $$X = (1+\alpha) \left[\frac{KY^2}{2\alpha|Q|} - \frac{0.26|Q|}{\alpha K} \right] \qquad 3.40$$

and for interface $$X = (1+\alpha) \left[\frac{\alpha K Y^2}{2|Q|} - \frac{0.26|Q|}{\alpha K} \right] \qquad 3.41$$

3.3.6 Length of intrusion

Assuming that the equation 3.41 could be applied to aquifers of finite depth and length. Length of intrusion was obtained by putting X = L and Y = D in equation 3.41, where D is the depth of aquifer.

i.e. $$L = (1+\alpha) \left[\left(\frac{\alpha K D^2}{2|Q|} \right) - \left(\frac{0.26|Q|}{\alpha K} \right) \right] \qquad 3.42$$

3.3.7 Maximum rate of exploitation from aquifer

Equation for the interface was $X = (1+\alpha) \left[\frac{\alpha K Y^2}{2|Q|} - \frac{0.26|Q|}{\alpha K} \right]$

From this we get $\frac{0.52|Q|^2}{\alpha K} + \frac{2X\,|Q|}{(1+\alpha)} - \alpha K Y^2 = 0$ 3.43

The standard form of the equation is $ax^2 + bx + C = 0$

Comparing the equation 3.43 we get

$a = 0.52/\alpha K$

$b = 2x/(1+\alpha)$

$c = -\alpha k y^2$

The solution Q is given by $Q = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

Thus Q can be calculated with the depth of the well from the mean sea level and its distances from the coast. The value of Q is expressed as Q_F which is less than the present aquifer discharge Q_I. The difference between Q_I and Q_F would be the maximum rate of exploitation from the aquifer.

3.4 Advancement of interface with increased exploitation of ground water

The boundary conditions maintaining a steady interface rarely remain constant. Any change in the boundary conditions will destroy the state of equilibrium and the interface profile will pass through a state of transient condition till a new equilibrium position is established. The excessive withdrawal from pumping wells, irregular recharging of the aquifers, storage of water in reservoirs causing variations in levels of surface source feeding the aquifer are the main sources which generally cause the movement of the interface. All these agencies causing the movement have a unique effect on varying the fresh water discharge through the aquifer. Hence any possible movement can be attributed to a change in the fresh water flow. When the discharge is decreased the intruded sea water wedge moves further into the aquifer and consequently it is termed as an advancing interface. On the other hand an increase in discharge creates a retreating interface.

The phenomenon of the movement of the interface due to a change in discharge caused by fluctuations in surface source level or due to pumping or recharging from or into the aquifer leads to a problem of solving nonlinear partial differential equations of higher order. The equations in this case do not come under any typical form for which solutions are available. Further, the equations are so complicated that it is practically impossible to arrive at explicit solutions. Numerical solutions of such equations are possible, but involve lengthy computations necessitating digital computers with large memory capacity. Under these circumstances it is considered that a simplification of the phenomenon by assuming an instantaneous steady nature of the interface will lead to simple situations. Such an assumption reduces the problem to that of solving ordinary differential equations.

A quasi-steady state analysis often becomes handy for solving many problems in ground water flow and yields fairly accurate results for an otherwise complicated problem. A partial justification of this assumption stems from the observation that temporal variations of flow characteristics are much smaller than spatial ones. (Koshina, 1962)

The temporal variation of interface is beyond the scope of the present study. The final positions of the interface can be located by making use of the principle mentioned above. So for any value of fresh water discharge the final position of interface will be obtained by substituting the appropriate values of fresh water discharge in equation 3.42.

3.5 Water quality test

The quality of ground water depends upon the quality of its source waters. The concentration and composition of dissolved constituents in a water determine the usefulness of the water for various purposes and the presence of some minerals beyond certain limits may make it unsuitable for irrigation, drinking or industrial purposes.

The quality of water depends upon the total quantity of dissolved solids depicted by parts per million, equivalent per million or specific conductance and the pH value. In the present study the quality of water is judged by the following characteristics.

1. Electrical conductivity
2. Sodium Adsorption Ratio
3. pH

3.5.1 Electrical conductivity

Electrical conductance bridge is used to determine electrical conductivity of ground water. It is a commonly used method because EC can be readily and precisely determined. This is generally represented in µmhos/cm. Chemically pure water has very low conductance. The specific conductance increases approximately linearly with the quantity of salts in solution and is different for each salt. Quality classification of water based on electrical conductivity is given below :

Water class	EC in µmhos/cm
C_1	< 250
C_2	250 - 750
C_3	750 - 2250
C_4	2250 - 5000

Low salinity water (C_1) can be used for irrigation. Medium salinity water (C_2) can be used if a moderate amount of leaching occurs. High salinity water (C_3) cannot be used on soils with restricted drainage. Very high salinity water (C_4) is not suitable for irrigation under ordinary conditions.

3.5.2 Sodium Adsorption Ratio (SAR)

The soluble inorganic constituents of irrigation waters react with soils as ions rather than as molecules. The principle cations are calcium, magnesium and sodium. Sodium does not affect the hardness of water though it is very important in determining the quality of irrigation waters. Concentration of sodium was obtained by Flame photometer. Concentrations of calcium and magnesium were determined by titration method. The sodium adsorption ratio is defined by the equation.

$$\mathrm{SAR} = \mathrm{Na}^{+}/\sqrt{(\mathrm{Ca}^{++} + \mathrm{Mg}^{++})/2}$$

Where Na^{+}, Ca^{++} and Mg^{++} represent the concentrations in milliequivalents per litre of the respective ions. Based on SAR the quality classification of water is given as follows.

Water class	SAR
S_1	< 10
S_2	10 - 18
S_3	18 - 26
S_4	> 26

Low medium water (S_1) can be used for irrigation. Medium sodium water (S_2) will present an appreciable sodium hazard in fine textured soils having high cation exchange capacity, especially under low leaching conditions, unless gypsum is present in the soil. High sodium water (S_3) may produce harmful levels of exchangeable sodium

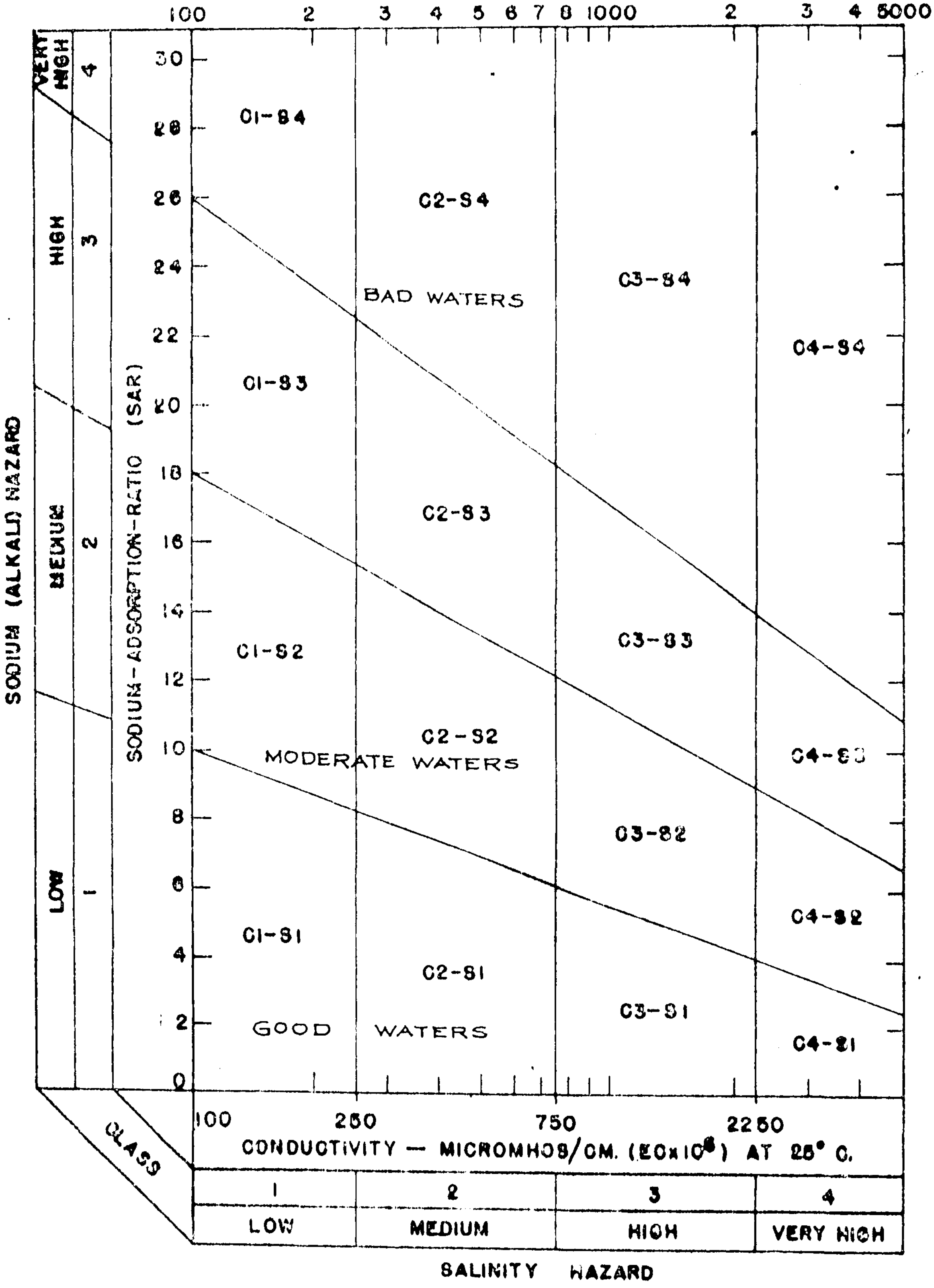


FIG. 3.9. DIAGRAM FOR CLASSIFICATION OF WATER.

in most soils and will require special soil management good drainage, high leaching and organic matter additions. Very high sodium water (S_4) is generally unsuitable for irrigation purposes. The diagram for the classification of irrigation waters is shown in Fig. 3.9. It is based on the electrical conductivity in micromhos per centimeter and the sodium adsorption ratio.

3.5.3 pH

pH is a scale indicating the acidity or alkalinity of aqueous solutions. It is conventionally defined as the negative logarithm of hydrogen ion concentration. pH can be determined by electrometrically or by indicators. The most prevalent instrument for measuring cell potentials is an electronic voltmeter known as a pH meter. pH value is a number from 1 to 14, which represents a logarithmic scale indicating the concentrations of hydrogen ions. pH 7 is the neutrality point of purewater at which the concentrations of hydrogen and hydroxyl ions are equal. pH values from 1 to 7 are used to indicate the acidity of the solution and numbers 7 to 14 indicate the alkalinity of the solution.

Results and Discussion

RESULTS AND DISCUSSION

The results of sea water intrusion studies for coastal aquifers have been discussed in the following sections.

4.1 Site at Nattika

Basic observations

Height of fresh water above the mean sea level was measured by taking levels. Figure 3.2 shows the measured values of the height of fresh water. Distance of selected wells from the shore were 188.59 m, 260.93 m and 348.53 m respectively. From the bore hole data given in Appendix I, the depth of the aquifer was found to be 8.81 m. The coefficient of permeability of the aquifer was calculated as 120.92 m/day with reference to the lithologocal data.

4.1.1 Aquifer discharge (QI)

The aquifer discharge at the time of observation was found to be 3.14 m^3/day/metre width of coast line. The length of intrusion corresponding to the aquifer discharge was calculated as 38.02 m. Figure 4.1 shows the length of intrusion when the aquifer discharge is 3.14 m^3/day/metre width of coast line. The selected wells were at a distance of 188.59 m, 260.93 m and 348.53 m respectively from the shore. The selected wells were found to lie beyond the length of

Table 4.1. Estimation of length of intrusion for various depth when QI = 3.14 m^3/day/metre width of coast line

Depth (m)	Length of intrusion (m)
1	0.22
2	1.70
3	4.15
4	7.60
5	12.02
6	17.44
7	23.83
8	31.21
8.81	38.02

Table 4.2. Chemical analysis of water

Sl. No.	Source of Water	Sodium Adsorption Ratio	pH	Electrical Conductivity (μmhos/cm)	Calcium (m.eq/litre)	Magnesium (m.eq/litre)	Calcium + Magnesium (m.eq/litre)	Sodium (m.eq/litre)
1	Well No. 1	1.329	6.55	300	1.2675	0.22475	1.49225	1.148
2	Well No. 2	1.356	7.65	400	1.979	0.12675	2.10575	1.391
3	Well No. 3	0.85	8.00	400	2.135	0.117	2.252	0.904

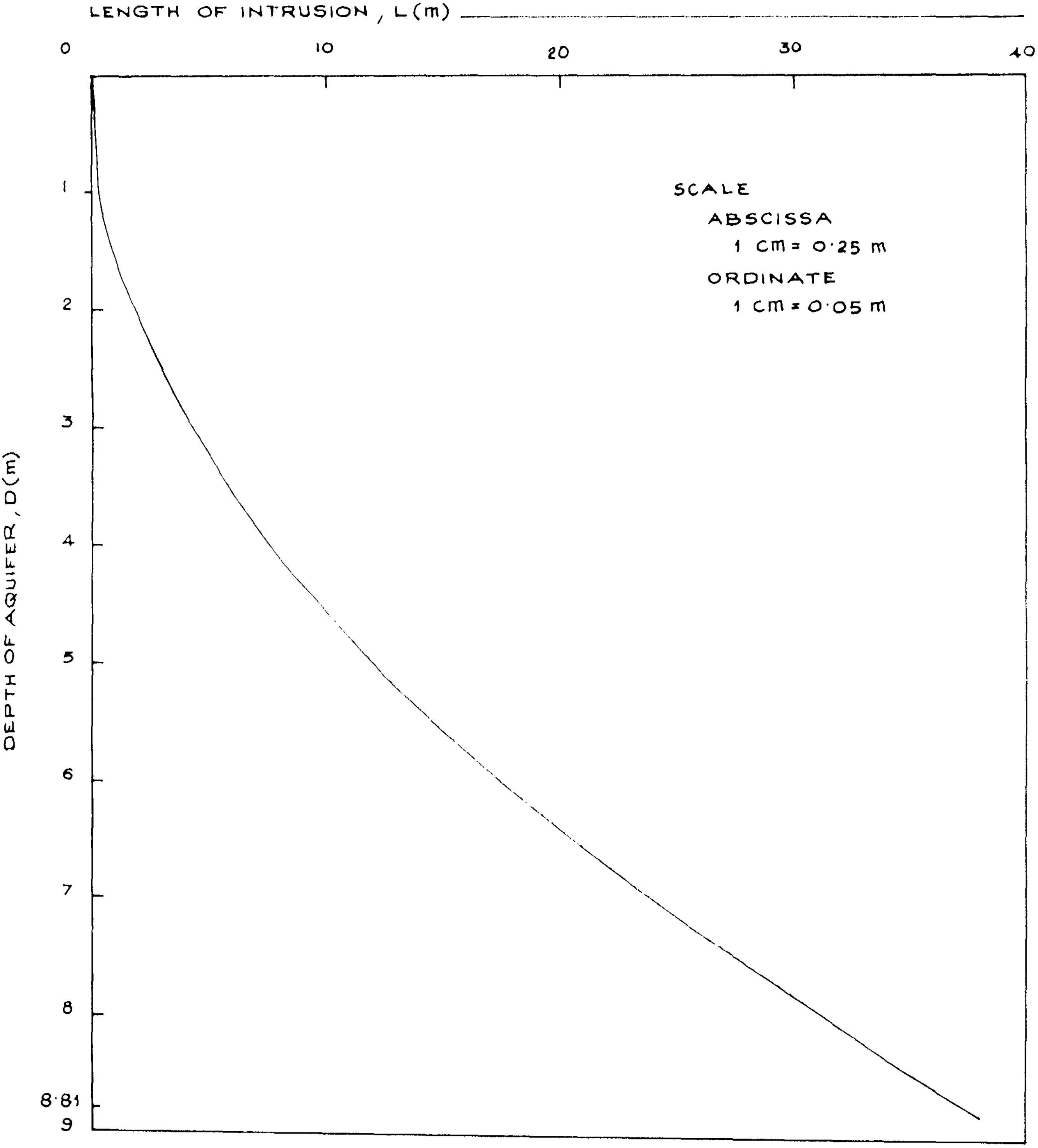


FIG.4·1. GRAPH SHOWING THE POSITION OF INTERFACE WHEN $Q_1 = 3{\cdot}14 m^3$/DAY/m. WIDTH AT NATTIKA.

intrusion corresponding to the present aquifer discharge. Therefore at the time of observation there was no problem of salinity intrusion.

Water analysis data is given in Table 4.2. The water samples from each well were analysed for pH, EC, Ca^{++}, Mg^{++} and Na^{+} contents. The value of pH varied from 6.55 to 8. EC varied from 300 to 400 µmhos/cm and SAR varied from 0.85 to 1.356. Based on the diagram for the classification of irrigation waters, the water samples come under C_2 - S_1 class. It indicated that the water was not rich in salt content.

Since the tidal range of Kerala coastal tracts is only 1 m, the dispersion of the interface is very small and thus it can be neglected. Therefore at this site, there was no salinity intrusion problem beyond 38.02 m length from the coast.

4.1.2 Maximum pumping rate (Q_p)

A computer programme was used to tabulate the maximum pumping rate of fresh water corresponding to different depth of wells. Table 4.3 gives the maximum pumping rate of fresh water at a distance of 188.59 m, 260.93 m and 348.33 m respectively. Figures 4.2, 4.3 and 4.4 show the position of the interface when the length of intrusions are 188.59 m, 260.93 m and 348.33 m respectively. The length of intrusion for various pumping rates were calculated and are given in Table 4.5. A graph with Q_p Vs. L was plotted. Figure 4.5 gives the pumping rates of various length of intrusions. Figures 4.6 to 4.9 show the length of intrusions

Table 4.3. Computation of maximum pumping rate for various distances from the coast

Depth (m)	Maximum pumping rate (m^3/day/metre width)		
	X = 188.59 m	X = 260.93 m	X = 348.33 m
1.0	3.1318390	3.1340568	3.1355648
1.5	3.1214604	3.1266055	3.1298876
2.0	3.1071787	3.1162269	3.1222589
2.5	3.0886390	3.1028321	3.1121464
3.0	3.0661077	3.0865102	3.0999048
3.5	3.0393183	3.0671721	3.0855343
4.0	3.0085373	3.0449955	3.0688577
4.5	2.9736757	3.0197144	3.0498743
5.0	2.9346449	2.9915056	3.0289397
5.5	2.8915336	2.9603696	3.0055213
6.0	2.8443418	2.9262178	2.979938
6.5	2.7929807	2.8891385	2.9521201
7.0	2.7375393	2.8490431	2.9221373
7.5	2.6780174	2.8060205	2.8900256
8.0	2.6143260	2.7599819	2.855430
8.81	2.5025561	2.6791704	2.7949324

Table 4.4. Position of different length of intrusions for various aquifer depth

Depth (m)	Length of intrusions (m)		
	L_1 = 188.59 m	L_2 = 260.93 m	L_3 = 348.53 m
1	2.37	3.25	4.40
2	9.67	13.14	17.68
3	21.83	29.63	39.81
4	38.86	52.70	70.80
5	60.75	82.37	110.64
6	87.51	118.63	159.06
7	119.13	161.48	216.89
8	155.61	210.93	283.30
8.81	188.59	260.93	343.53

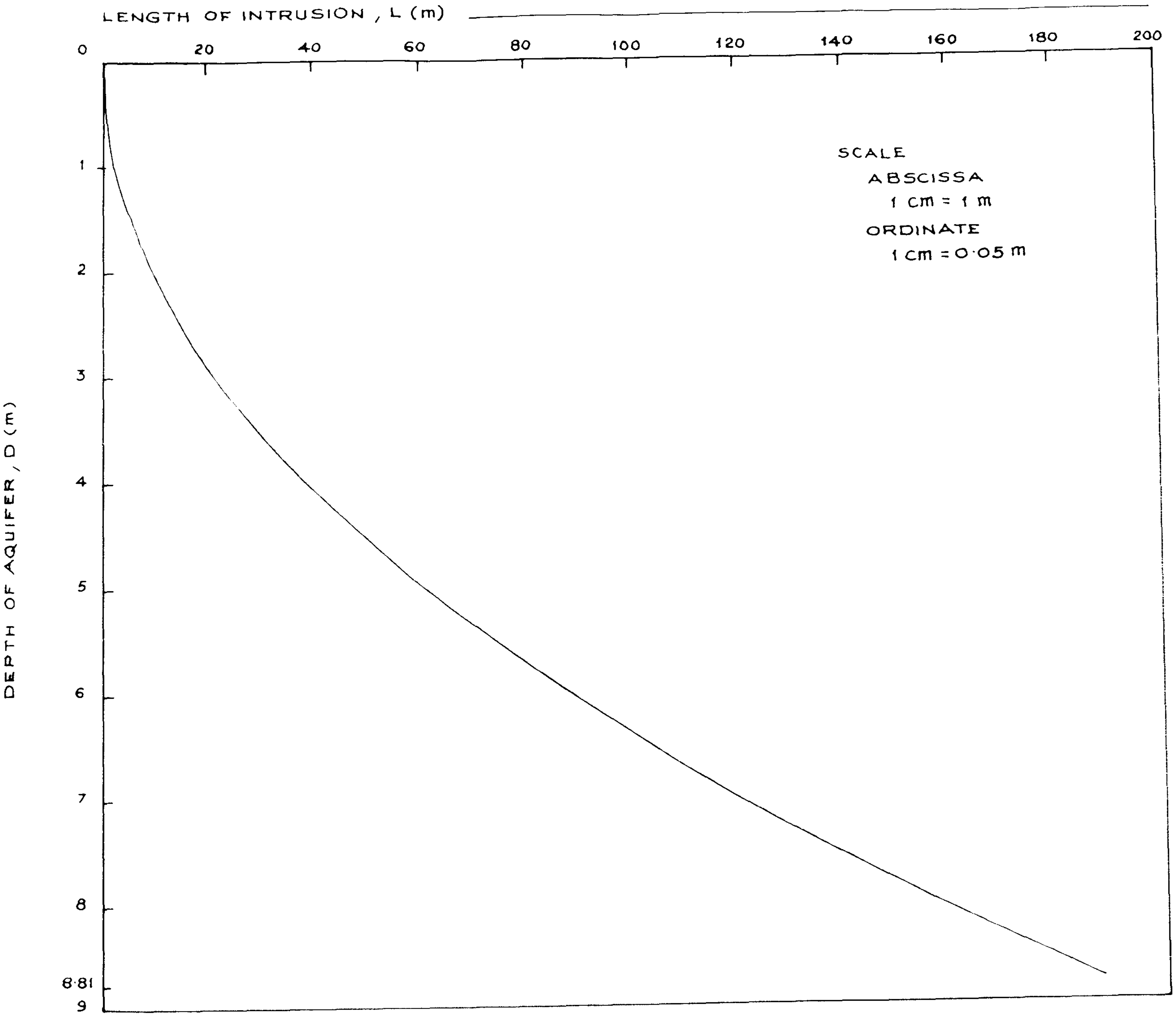


FIG.4·2 GRAPH SHOWING THE POSITION OF INTERFACE WHEN X = 188·59 m AT NATTIKA

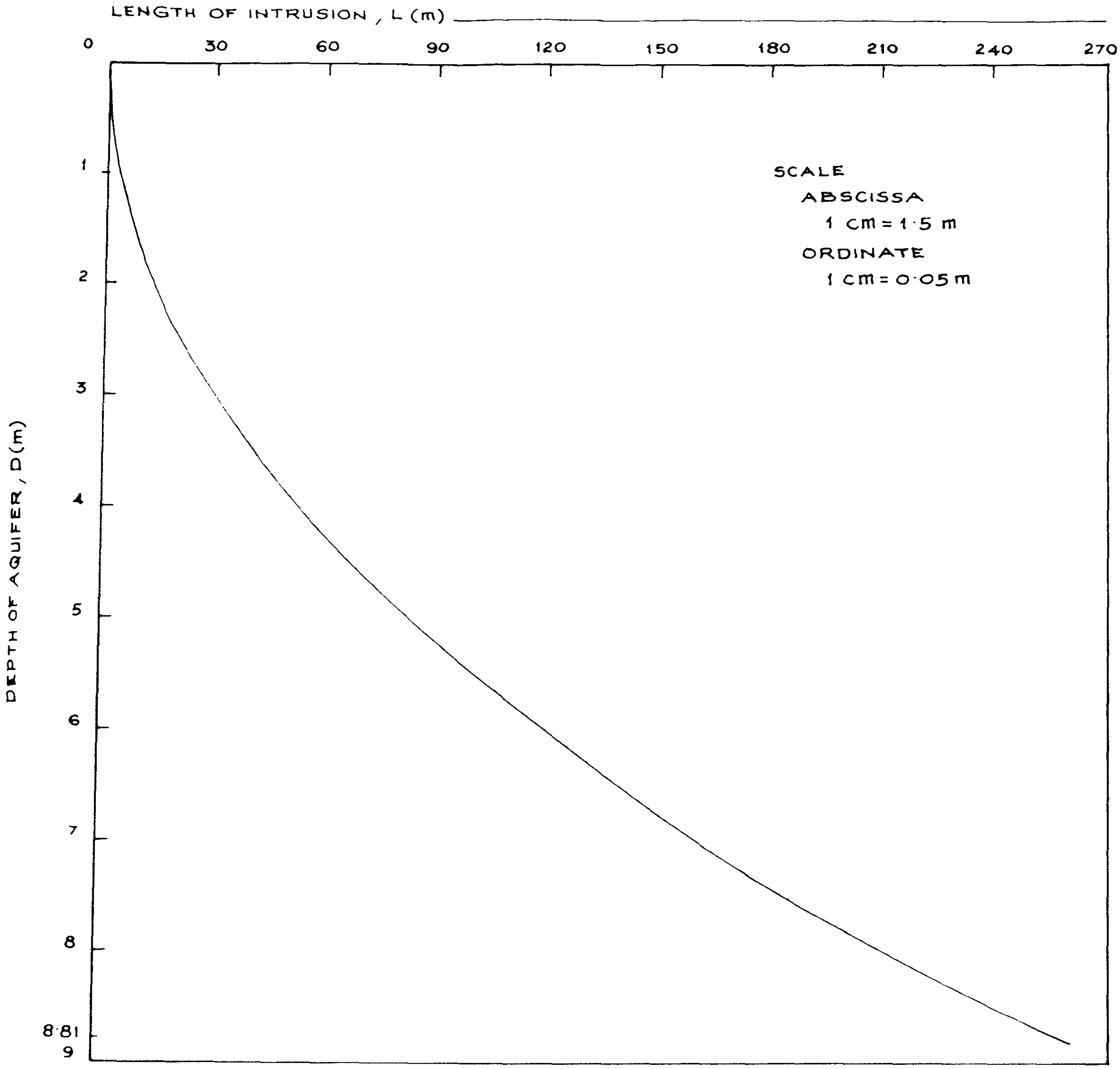


FIG.43. GRAPH SHOWING THE POSITION OF INTERFACE WHEN X = 260·93 m. [illegible]

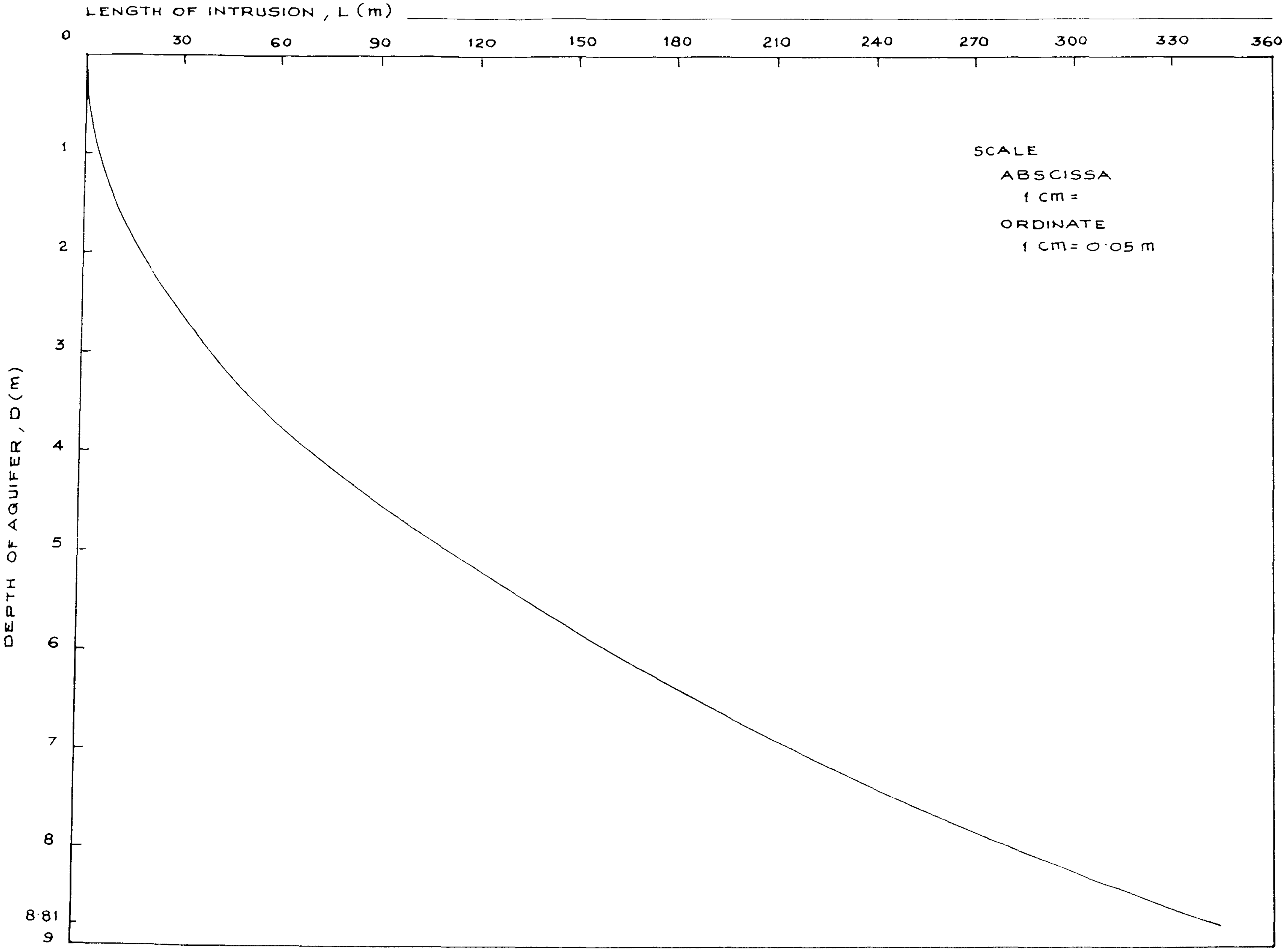


FIG.4.4 GRAPH SHOWING THE POSITION OF INTERSPACE WHEN $X = 343 \cdot 53$ AT [illegible]

Table 4.5. Computation of length of intrusion for various pumping rate

Maximum pumping rate (m^3/day/metre width)	Length of intrusion (m)
0.5	45.32
1.0	56.00
1.5	73.18
2.0	105.38
2.5	187.83
2.6	222.64
2.7	273.26
2.8	353.65
2.9	501.02
3.0	859.00

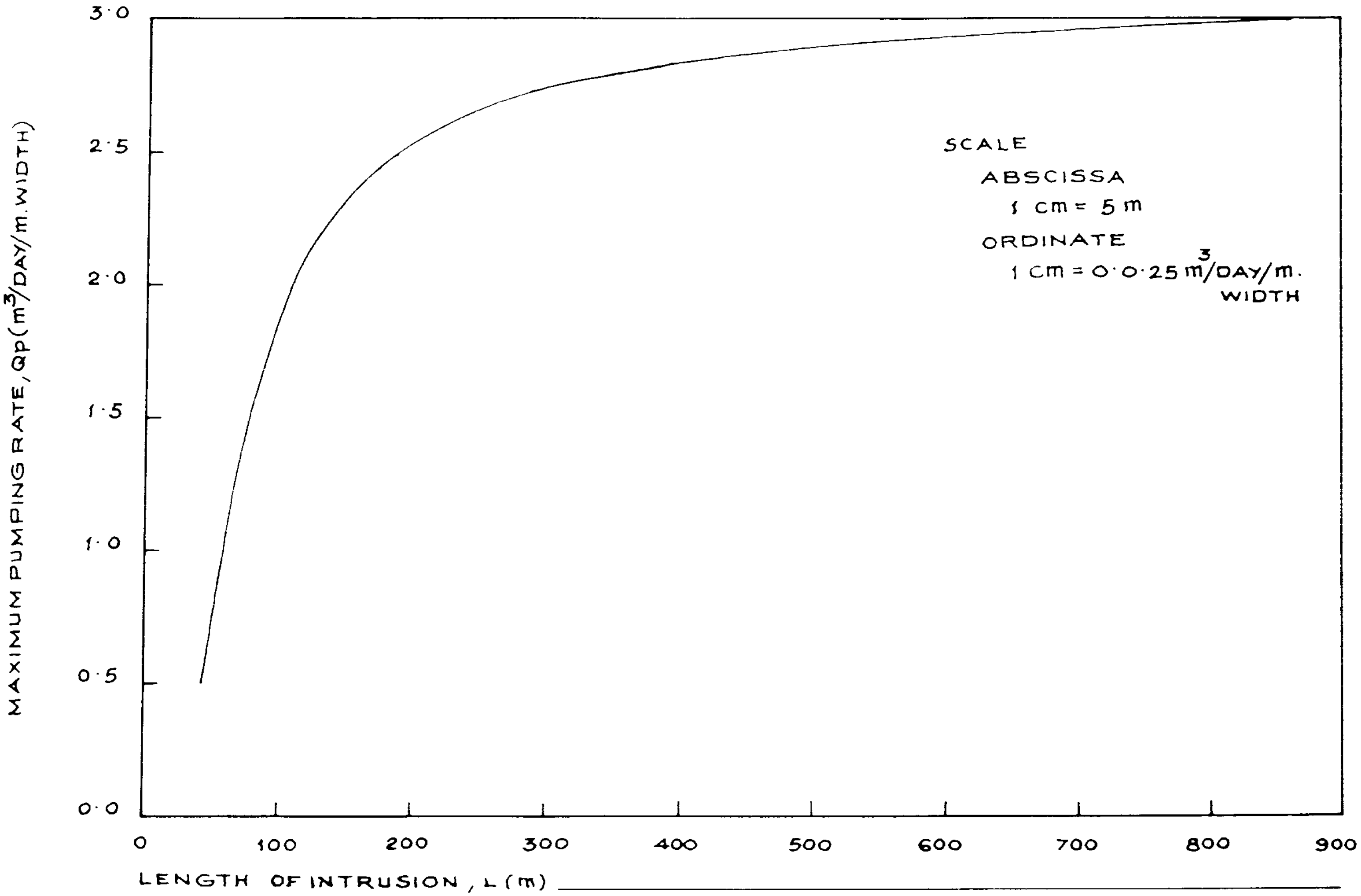


FIG.4.5 GRAPH REPRESENTING THE RELATION BETWEEN MAXIMUM PUMPING RATE AND LENGTH OF INTRUSION *AT NATTIKA.*

Table 4.6. Estimation of length of intrusion for various aquifer depth when $Q_p = 1\ m^3$/day/metre width

Depth (m)	Length of intrusion (m)
1	0.5
2	2.7
3	6.3
4	11.4
5	18.0
6	25.8
7	35.3
8	46.1
8.81	56.0

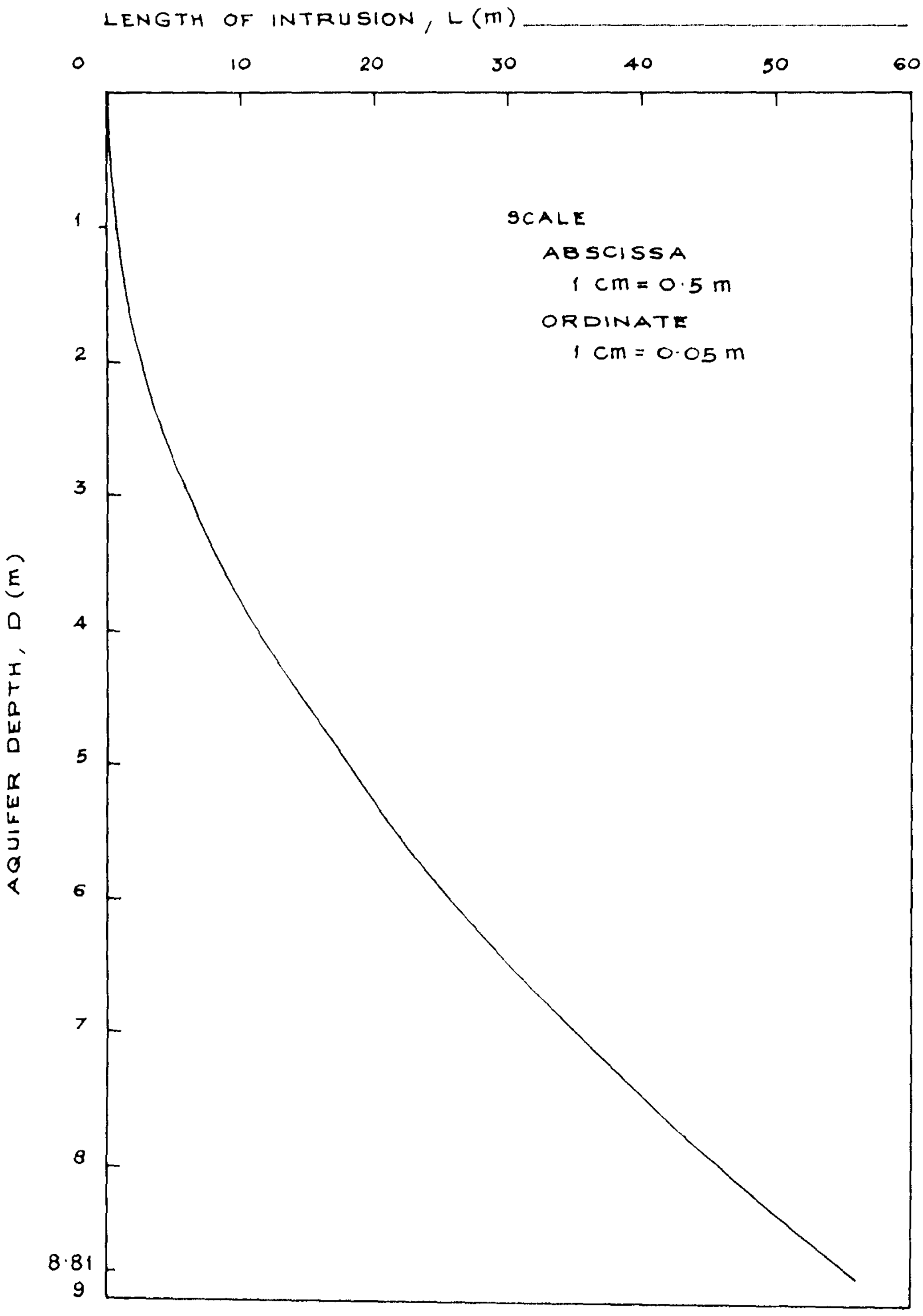


FIG.4·6. GRAPH SHOWING THE POSITION OF INTERFACE WHEN MAXIMUM PUMPING RATE = 1 m^3/DAY/m.WIDTH. AT NATTIKA.

Table 4.7. Estimation of length of intrusion for various aquifer depth when $Q_p = 1.5 m^3$/day/metre width

Depth (m)	Length of intrusion (m)
1	0.8
2	3.63
3	8.34
4	15.0
5	23.43
6	33.80
7	46.06
8	60.21
8.81	73.05

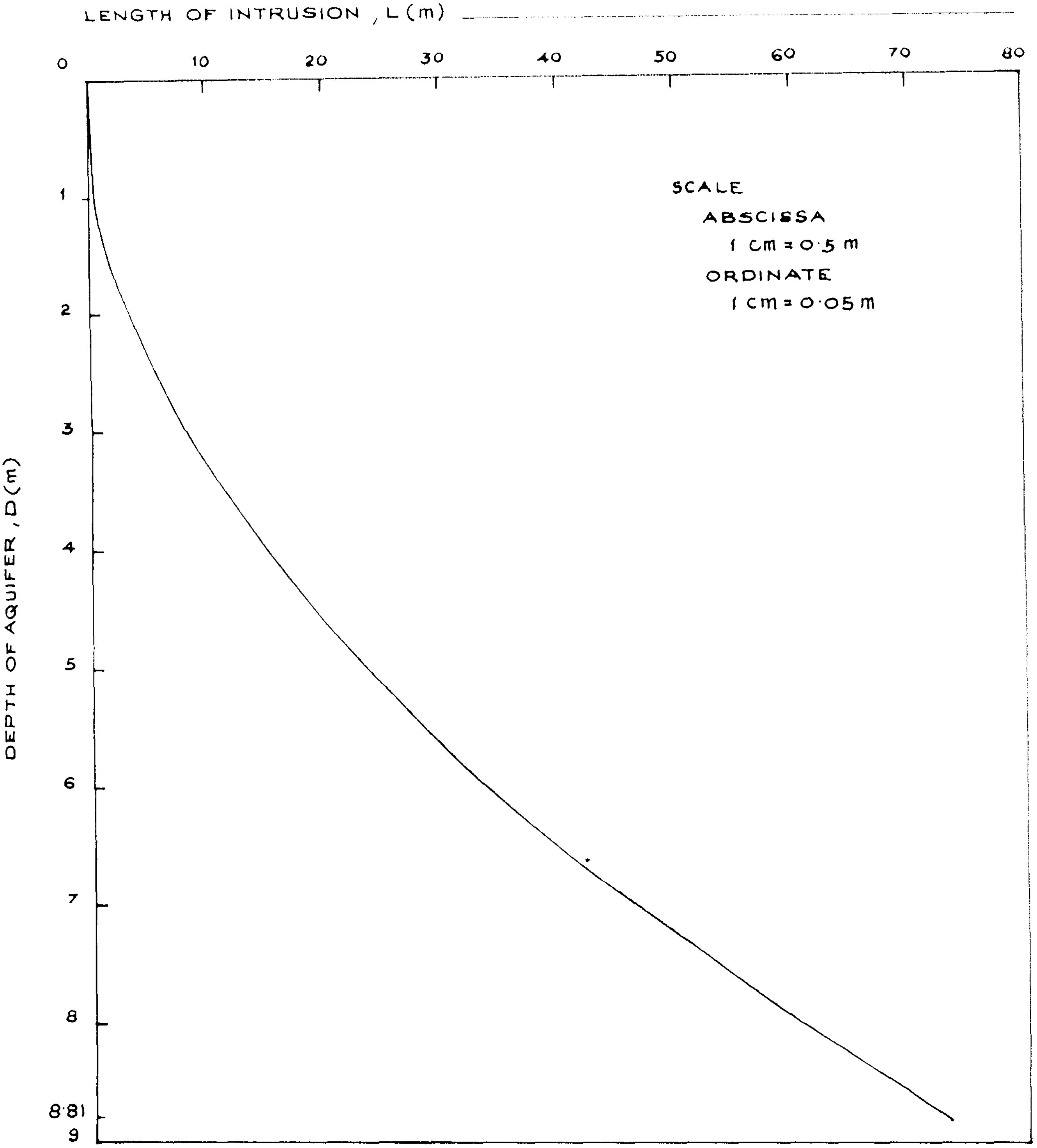


FIG.4·7. GRAPH SHOWING POSITION OF INTERFACE WHEN $Q_p = 1{\cdot}5\ m^3$/DAY/m. WIDTH AT NATTIKA.

Table 4.8. Estimation of length of intrusion for various aquifer depth when $Q_p = 2m^3$/day/metre width

Depth (m)	Length of intrusion (m)
1	1.26
2	5.34
3	12.13
4	21.65
5	33.87
6	48.83
7	66.50
8	86.88
8.81	105.39

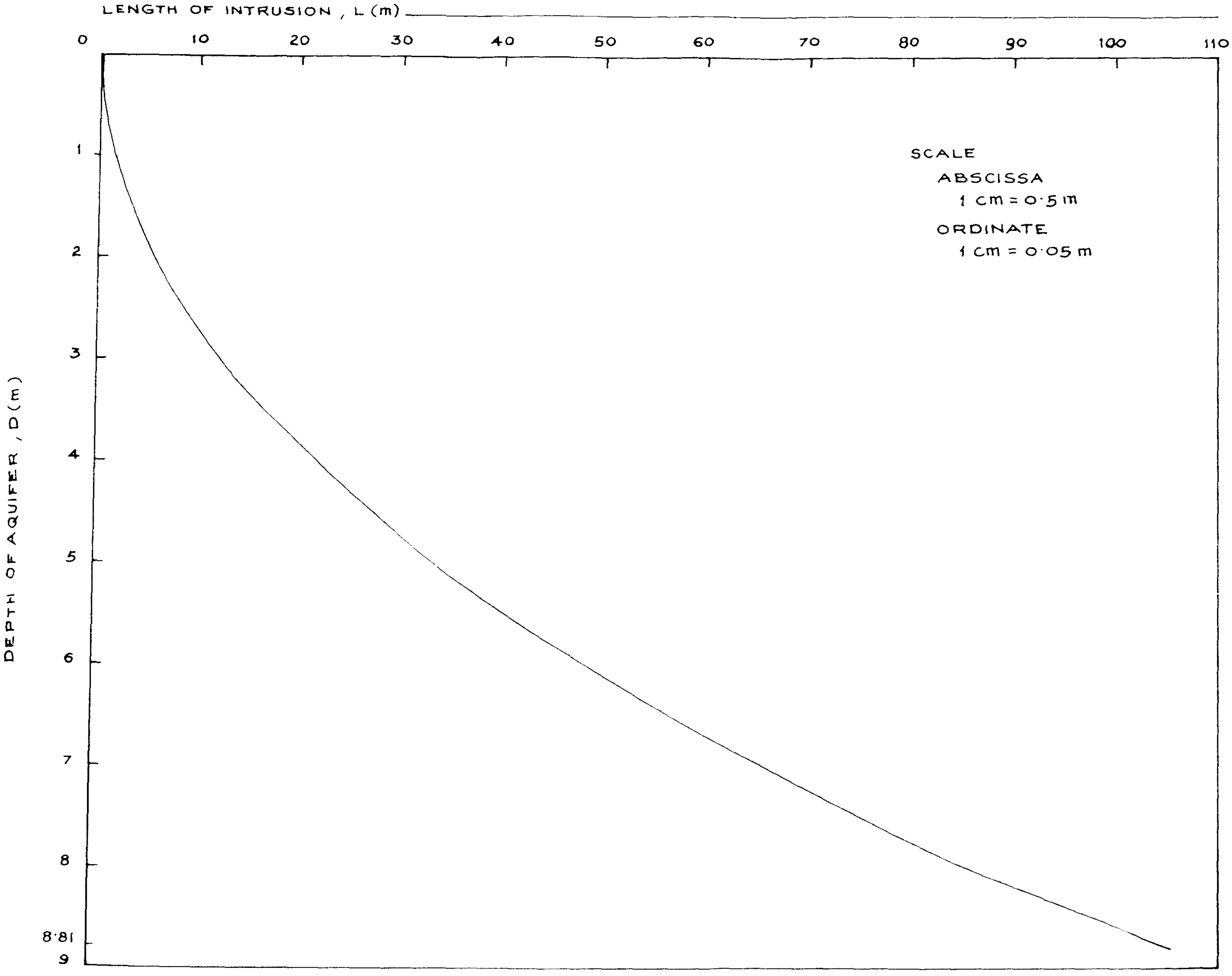

LENGTH OF INTRUSION , L (m)
0
10
20
30
40
50
60
70
80
90
100
110
DEPTH OF AQUIFER , D (m)
1
2
3
4
5
6
7
8
8·81
9
SCALE
ABSCISSA
1 cm = 0·5 m
ORDINATE
1 cm = 0·05 m

Table 4.9. Estimation of length of intrusion for various aquifer depth when $Q_p = 2.5\ m^3$/day/metre width

Depth (m)	Length of intrusion (m)
1	2.4
2	9.6
3	21.7
4	38.6
5	60.4
6	87.4
7	118.5
8	154.8
8.81	187.7

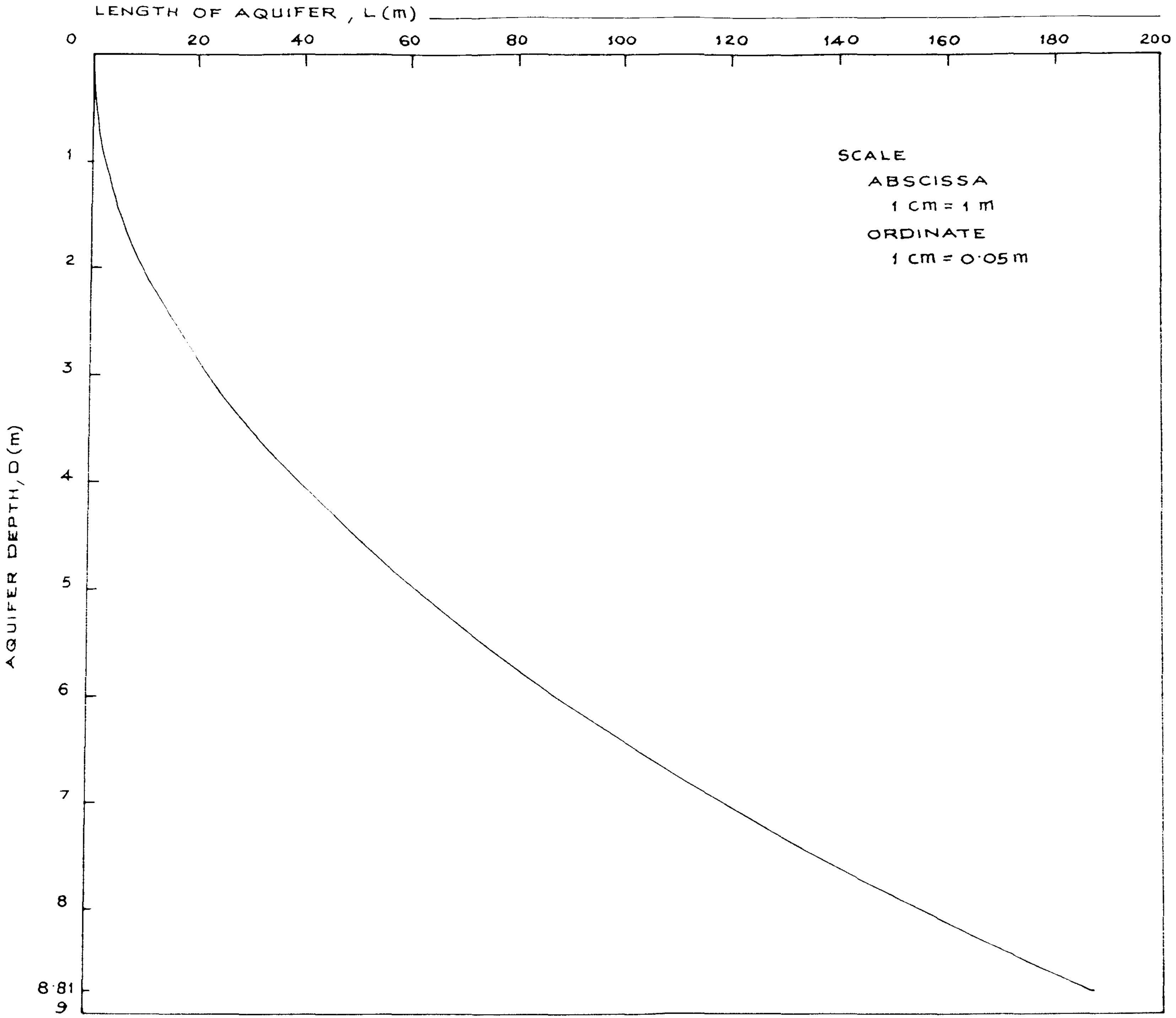


FIG.4·9. RELATION BETWEEN LENGTH OF INTRUSION AND DEPTH OF AQUIFER WHEN $Q_o = 2{\cdot}5\,m^3$/DAY/m WIDTH AT NATTIKA.

Table 4.10. Advancement of saltwater wedge with incresed groundwater exploitation

Depth (m)	Aquifer discharges (m^3/day/metre width)				
	Q = QI	Q = 3/4QI	Q = 2/3QI	Q = QI/2	Q = QI/4
1	0.22	0.45	0.56	0.85	1.90
2	1.70	2.42	2.78	3.81	7.82
3	4.15	5.71	6.49	8.74	17.69
4	7.60	10.32	11.67	15.65	31.50
5	12.02	16.24	18.34	24.53	49.26
6	17.44	23.48	26.49	35.39	70.96
7	23.83	32.04	36.13	48.21	96.61
8	31.21	42.00	47.24	64.55	126.21
8.81	38.02	50.87	57.33	76.45	153.08

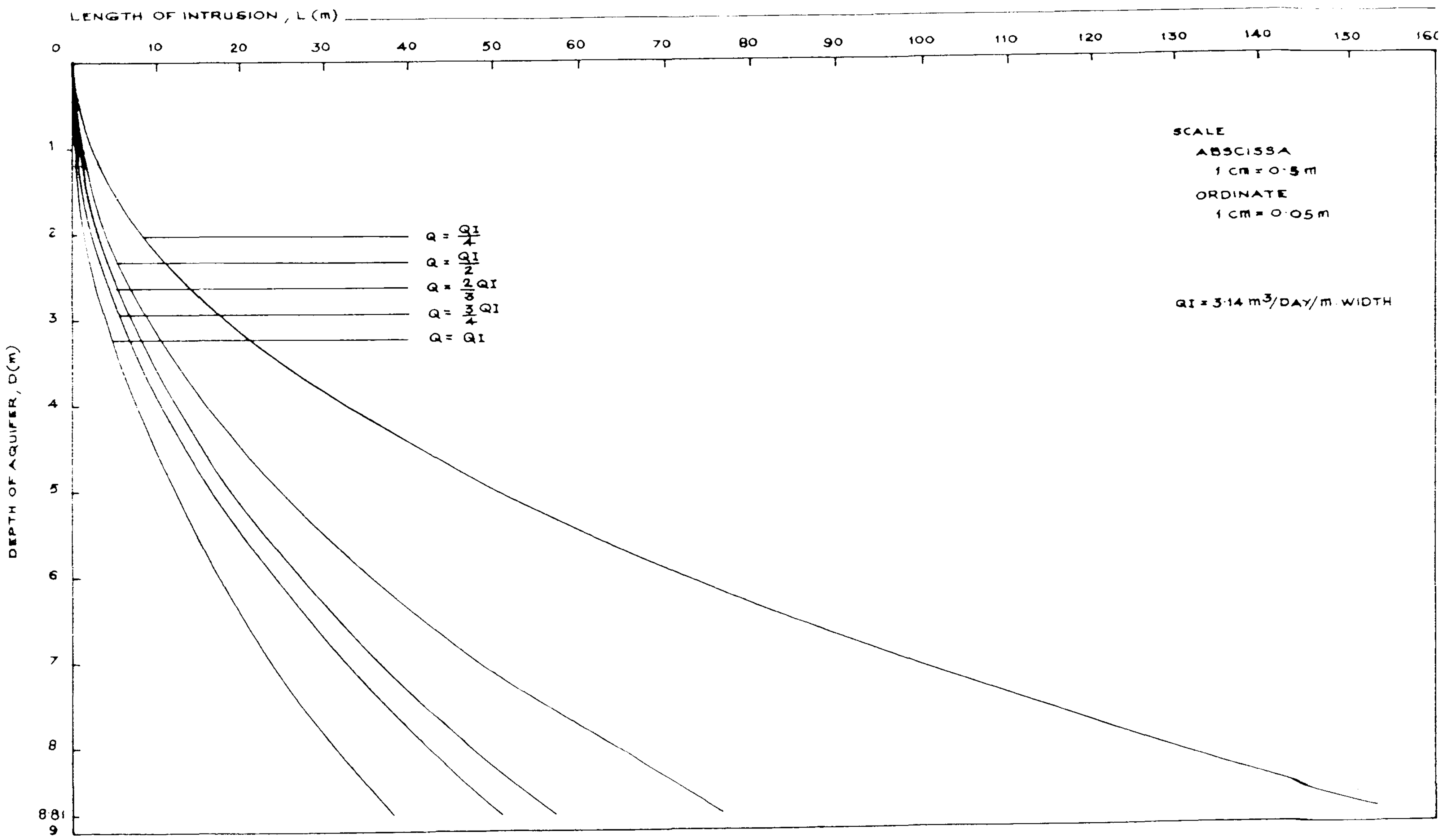


FIG 4·10. GRAPH SHOWING ADVANCEMENT OF SALT WATER WEDGE WITH INCREASED GROUND WATER EXPLOITATION. A. [illegible].

when pumping rates are 1 m^3/day/metre width, 1.5 m^3/day/metre width, 2m^3/day/metre width and 2.5 m^3/day/metre width respectively. With reference to these graphs we can fix the depth of the wells without fear of salinity.

4.1.3 Advancement of saltwater wedge with increased ground water exploitation

Figure 4.10 gives the positions of the interface for increased exploitation of ground water. The ground water exploitation was proposed at the rates of QI/4, QI/3, QI/2 and 3/4QI, the seaward freshwater discharges were 3/4QI, 2/3QI, QI/2 and QI/4 respectively and the corresponding length of intrusions were found to be 4/3 L, 3/2 L, 2L and 4L respectively.

4.2 Site at Talikulam

Basic observations

Depth of aquifer was found to be 36.37 m from the bore hole data given in Appendix II. Figure 3.4 shows the measured fresh water heights. The selected wells were at a distance of 178.4 m, 283.78m and 326.79m respectively. The coefficient of permeability was calculated as 178.17 m/day.

4.2.1 Aquifer discharge (QI)

At the time of the observations, the aquifer discharge was 17.545 m^3/day/metre width of coast line. The length of intrusion corresponding to the aquifer discharge is shown in Fig. 4.11. The length of intrusion was calculated as 171.06m. Distance of the selected wells from the shore were 178.4 m, 283.78 m and 362.79 m respectively. These distances were more than the length of intrusion for the present aquifer discharge. So, there was no salt water intrusion at the time of observation.

Table 4.12 gives the water quality test results. The water samples were tested for pH, EC, Ca^{++}, Mg^{++} and Na^{+} contents. The results showed that the value of pH varied from 6.4 to 7.95, value of EC varied from 300 to 600 µmhos/cm and SAR varied between 0.78 to 1.860. According to the classification of irrigation waters, the collected water samples come under C_2 - S_1 class. So that the quality of water was good.

Since the dispersion of the interface was very small, there was no problem of salinity intrusion beyond 171.06 m length from the coast.

4.2.2 Maximum pumping rate (Q_p)

Maximum pumping rate of fresh water for different depth of wells were tabulated with a computer programme. Table 4.13 gives the maximum pumping rate of freshwater at a distance of 178.4m,

Table 4.11. Estimation of length of intrusion for various aquifer depth when QI = 17.545 m^3/day/metre width

Depth (m)	Length of intrusion (m)
5	2.18
10	11.87
15	28.01
20	50.61
25	79.61
30	115.19
35	157.16
36.37	171.06

Table 4.12. Chemical analysis of water

Sl. No.	Source of Water	Sodium Adsorption Ratio	pH	Electrical conductivity (μ mhos/cm)	Calcium (m.eq/litre)	Magnesium (m.eq/litre)	Calcium + Magnesium (m.eq/litre)	Sodium (m.eq/litre)
1	Well No. 1	0.856	7.45	500	2.886	0.3023	3.1883	1.078
2	Well No. 2	1.86	6.40	600	2.33	0.36075	2.69075	2.157
3	Well No. 3	0.78	7.95	300	1.4625	0.28275	1.74525	0.73

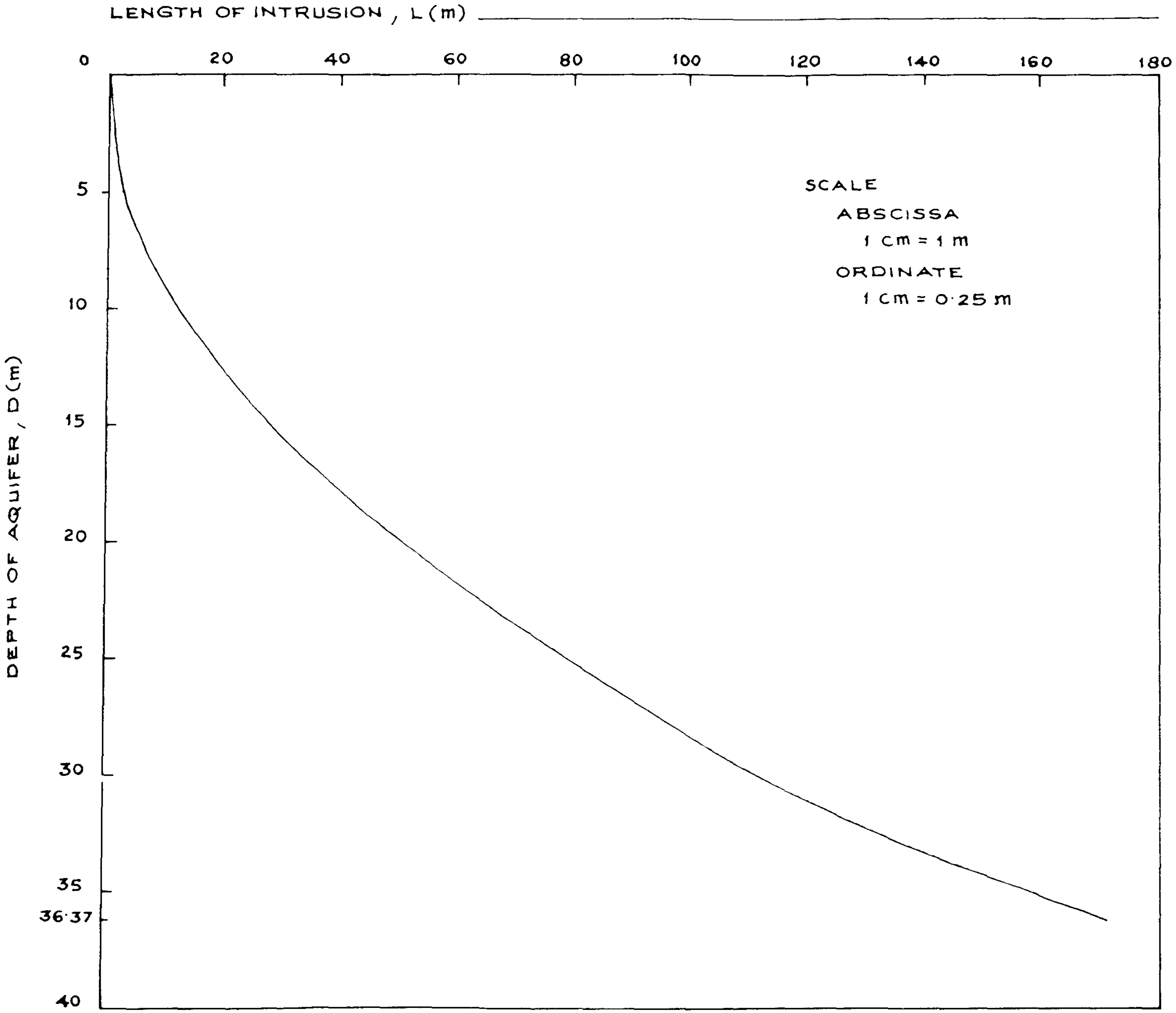


FIG.4·11. GRAPH SHOWING THE POSITION OF INTERFACE WHEN $Q_I = 17 \cdot 545\ m^3$/DAY/m.WIDTH

Table 4.13. Computation of maximum pumping rate for various distances from the coast

Depth (m)	Maximum pumping rate (m^3/day/metre width)		
	X = 178.4 m	X = 283.78 m	X = 362.79 m
1	17.532190	17.536896	17.538727
2	17.493763	17.512846	17.519905
4	17.340185	17.416124	17.444357
6	17.084396	17.255358	17.318357
8	16.726265	17.030024	17.142168
10	16.265924	16.740643	16.915787
12	15.703501	16.386694	16.638954
14	15.039129	15.968701	16.311932
16	14.272807	15.486662	15.934457
18	13.404798	14.940055	15.507052
20	12.435360	14.329402	15.028934
22	11.364496	13.654705	14.500887
24	10.192597	12.915961	13.922649
26	8.919795	12.113173	13.294221
28	7.546480	11.246601	12.615864
30	6.072784	10.316244	11.887053
32	4.498969	9.321843	11.108315
34	2.825555	8.263918	10.279640
36.37	0.713760	6.927854	9.232963

283.78m and 362.79m are shown in Figs. 4.12, 4.13 and 4.14 respectively. Table 4.15 shows the length of intrusion for various pumping rates. A graph of Q_p Vs. L was plotted. Figure 4.15 shows the maximum pumping rates for various length of intrusions. Figures 4.16 to 4.23 show the length of intrusions when pumping rates are 1 m^3/day/metre width, 2 m^3/day/metre width, 4m^3/day/metre width, 6m^3/day/metre width, 8 m^3/day/metre width, 10m^3/day/metre width, 12m^3/day/metre width and 14m^3/day/metre width respectively. Based on these graphs we can decide the depth of the wells without the problem of salinity.

4.2.3 Advancement of salt water wedge with increased ground water exploitation

Figure 4.24 illustrates the advancement of saltwater wedge with increased ground water exploitation at this site. It was found that when the aquifer discharge reduces to three-fourth of present aquifer discharge, the interface goes beyond the first selected well and when the aquifer discharge reduces to two-third of the present discharge, the interface comes nearer to the second selected well. If the aquifer discharge is reduced to half of the present discharge, the interface would come nearer to the third selected well and when the discharge is reduced to one-fourth of present discharge, the length of intrusion would be 688.21 m which is beyond the present selected wells. So it can be concluded that if the aquifer discharge is reduced from the present

Table 4.14. Position of different length of intrusions for various aquifer depth

Depth (m)	Length of intrusion		
	L_1 = 178.4 m	L_2 = 283.78 m	L_3 = 362.79 m
5	2.39	4.74	6.37
10	12.56	20.85	27.00
15	30.11	47.71	61.27
20	53.23	85.31	109.32
25	83.74	133.65	171.10
30	121.0	192.73	246.59
35	165.1	265.56	335.80
36.37	178.4	283.78	362.79

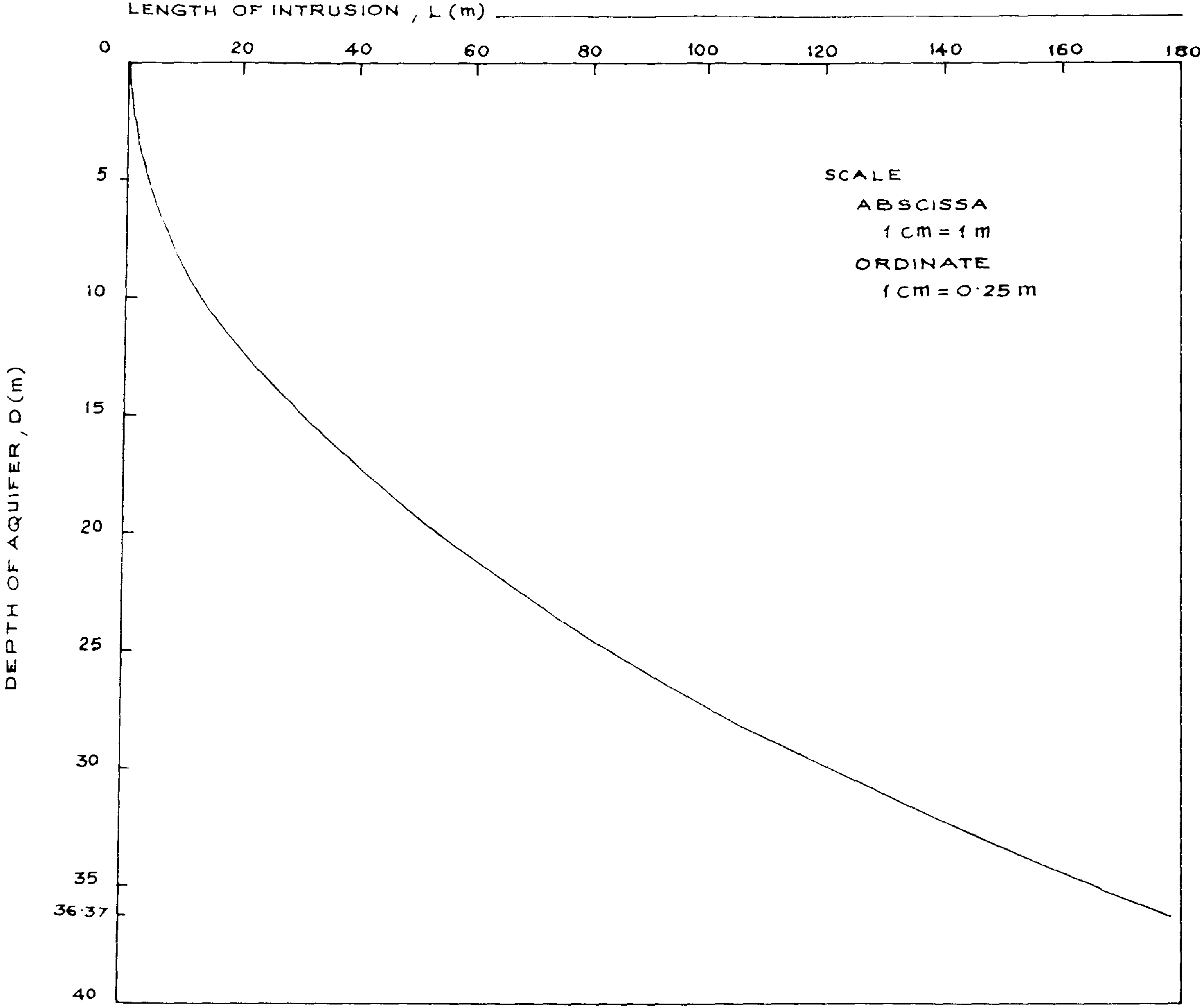


FIG.4·12 GRAPH SHOWING THE POSITION OF INTERFACE WHEN X = 178·4 m. AT PALIKULAM.

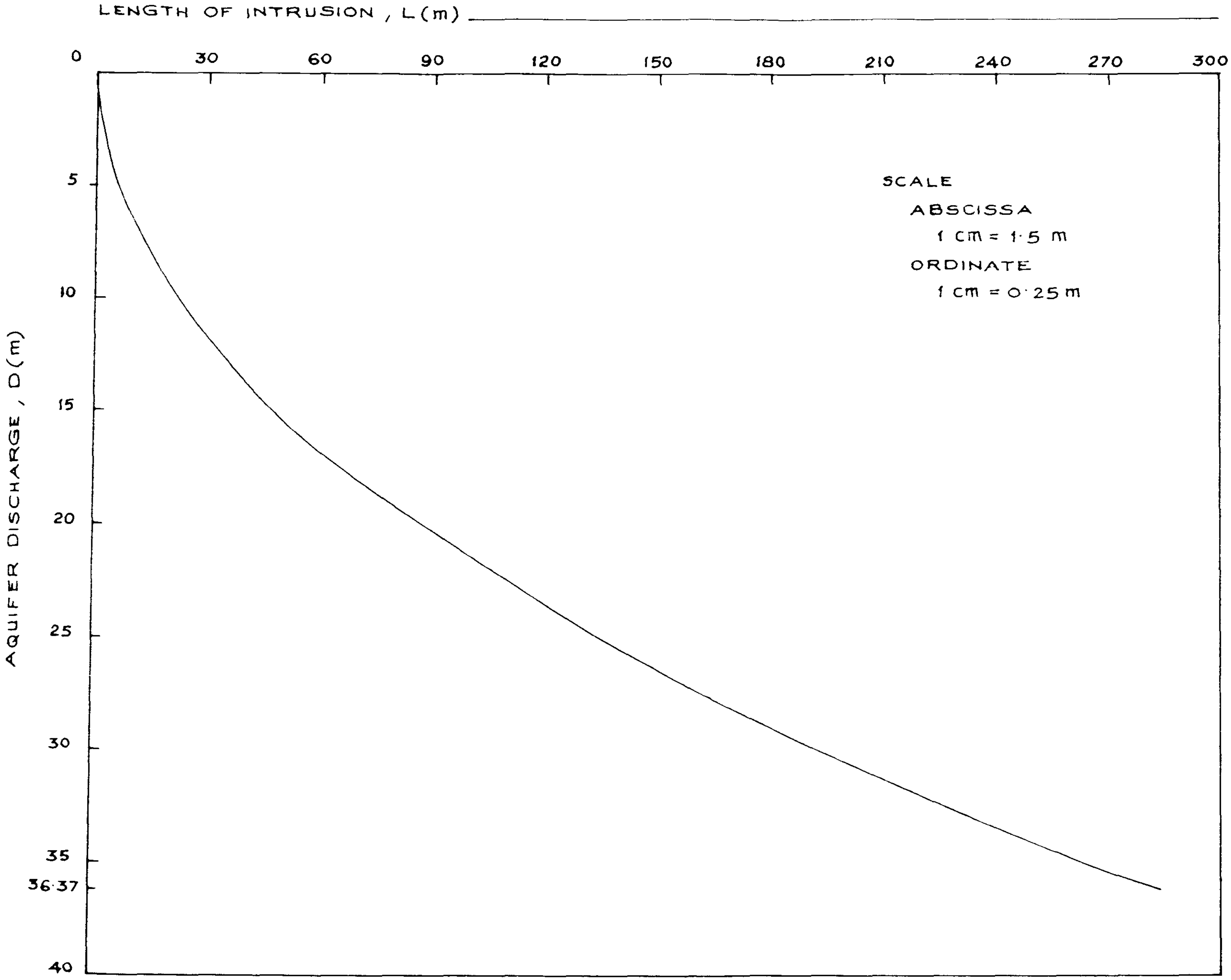


FIG 4·13 GRAPH SHOWING THE POSITION OF INTERFACE WHEN X = 283·78 m. AT PALIKULAM

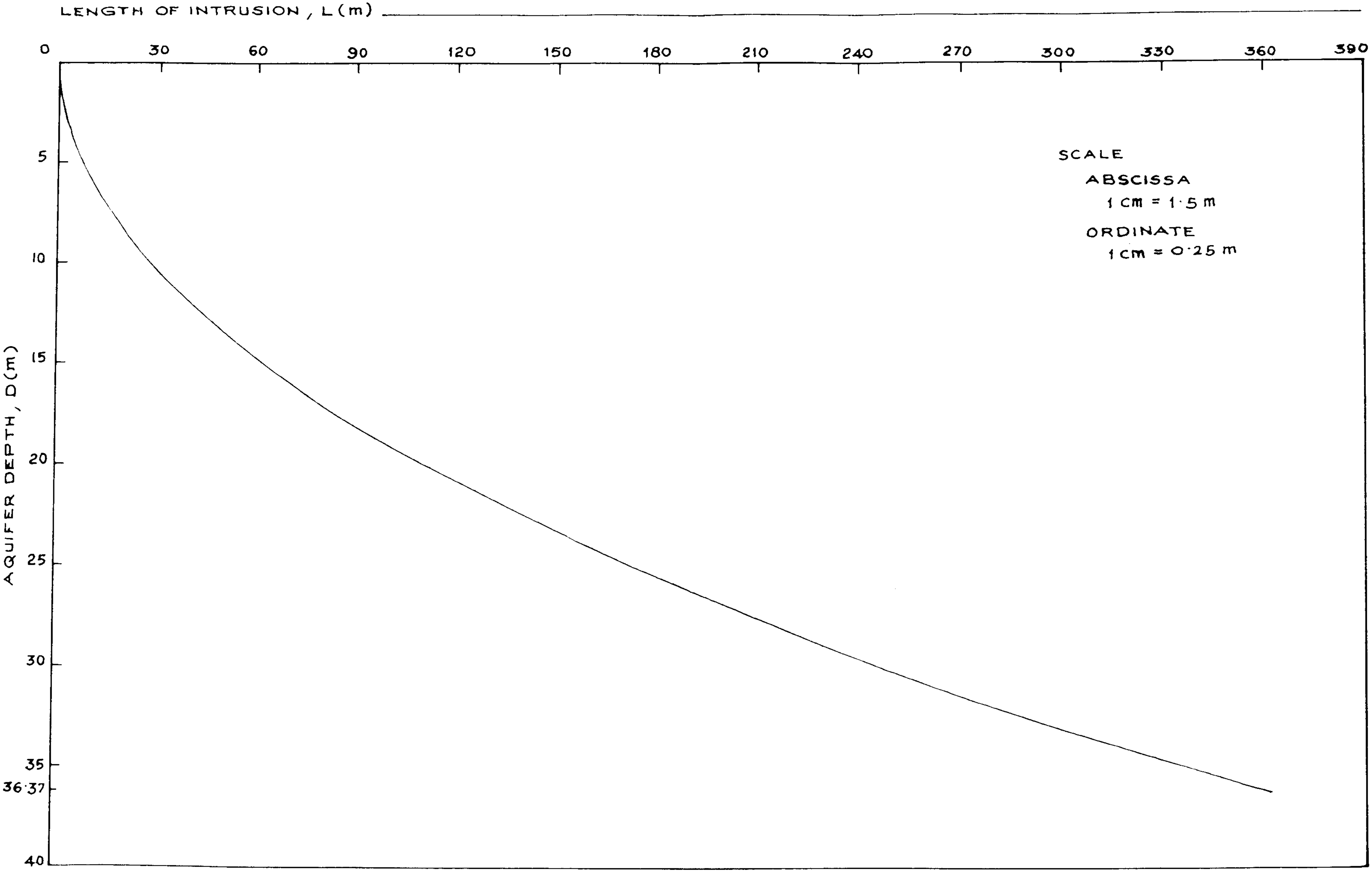


FIG.4.14 GRAPH SHOWING THE POSITION OF INTERFACE WHEN $x = 362{\cdot}79$ m AT TALIKULAM.

Table 4.15. Computation of length of intrusion for various pumping rate

Maximum pumping rate (m^3/day/metre width)	Length of intrusion (m)
14	851.59
12	544.24
10	399.77
8	315.79
6	260.86
4	222.12
2	193.32
1	181.52
0.5	176.14

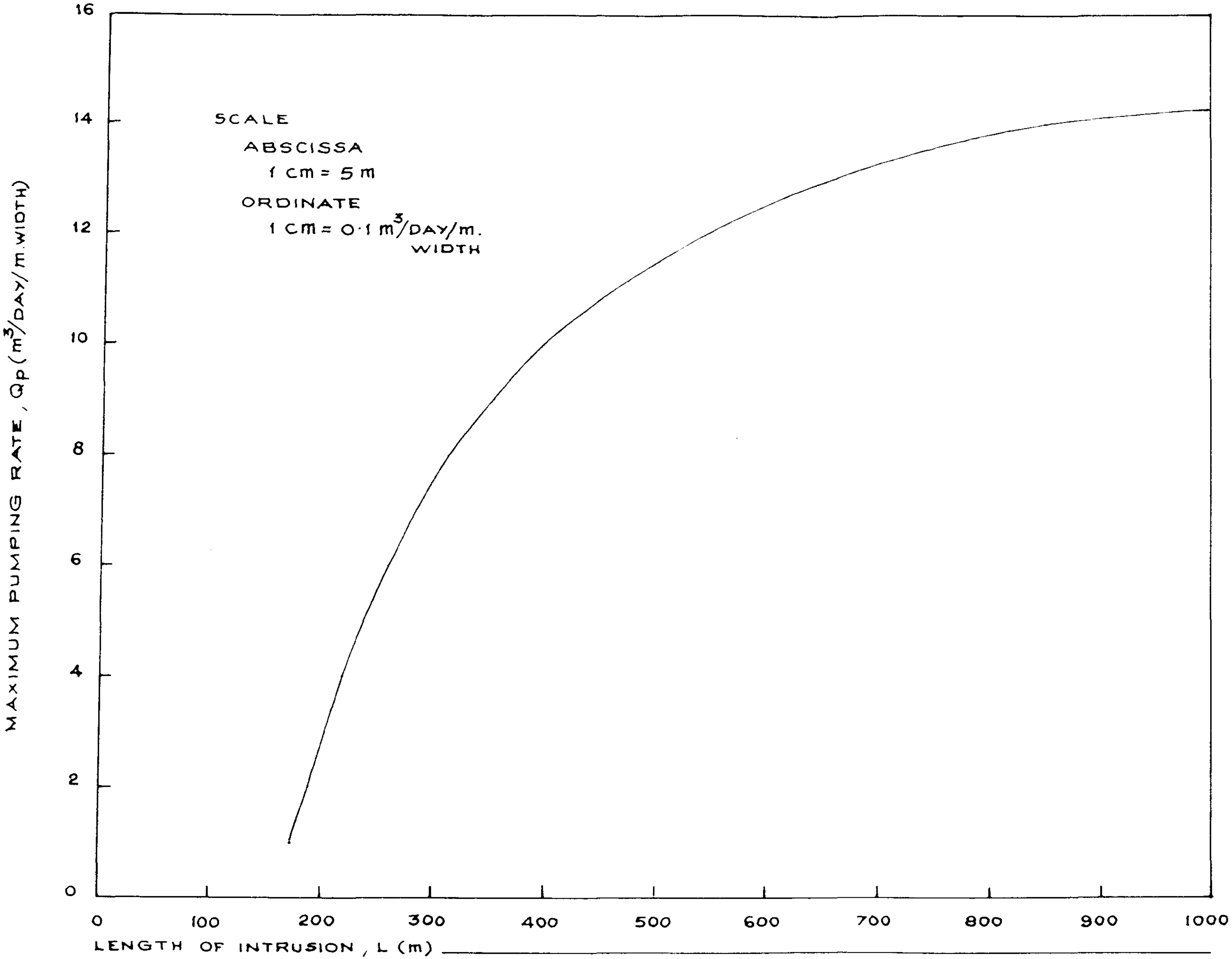


FIG 4·15 RELATION BETWEEN LENGTH OF INTRUSION AND MAXIMUM PUMPING RATE AT TALIKULAM.

Table 4.16. Estimation of length of intrusion for various aquifer depth when $Q_p = 1\ m^3$/day/metre width

Depth (m)	Length of intrusion (m)
5	2.46
10	12.81
15	30.05
20	54.2
25	85.24
30	123.18
35	168.02
36.37	181.52

Table 4.17. Estimation of length of intrusion for various aquifer depth when $Q_p = 2m^3$/day/metre width

Depth (m)	Length of intrusion (m)
5	2.74
10	13.73
15	32.05
20	57.70
25	90.68
30	131.00
35	178.60
36.37	193.00

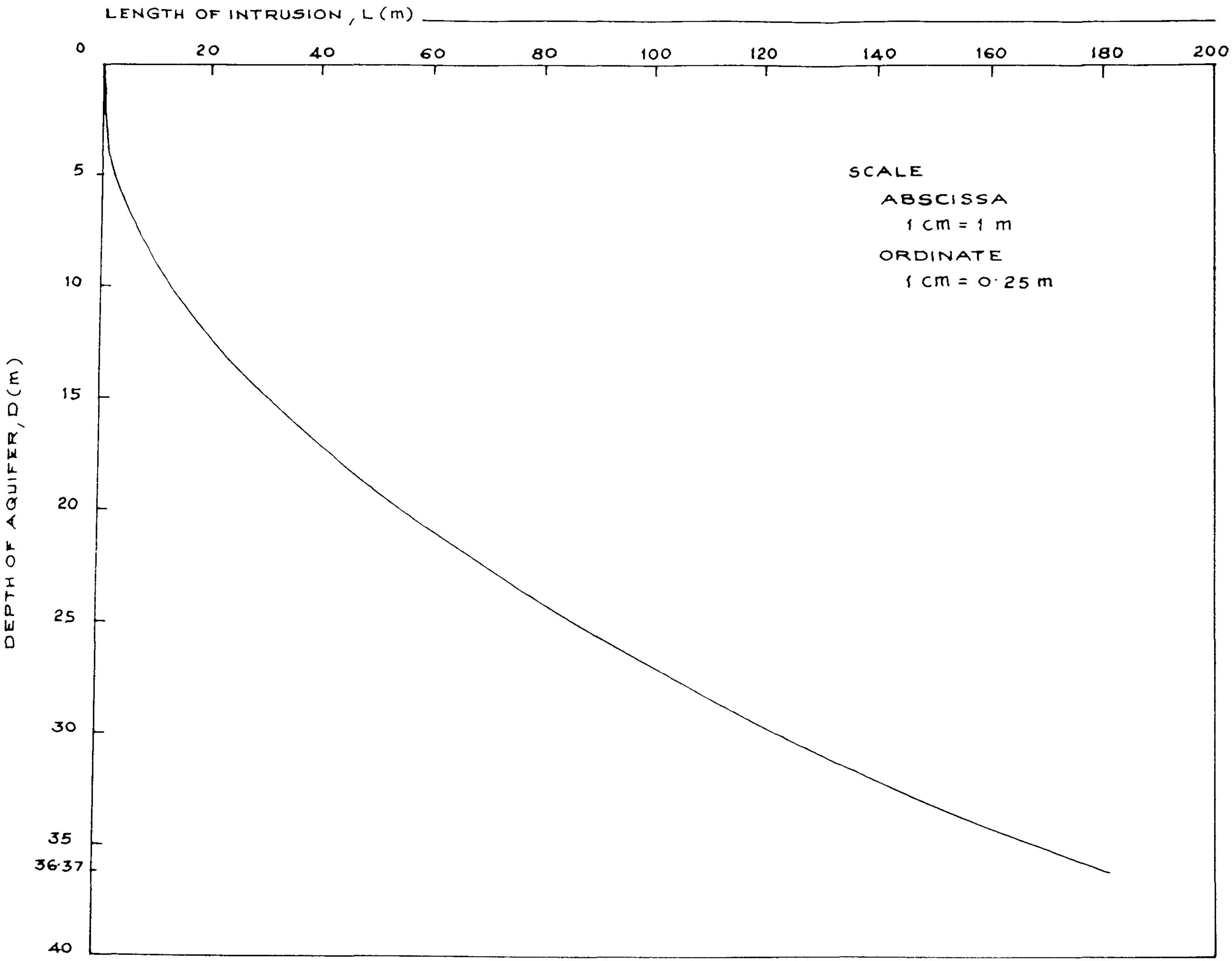


FIG. 4.16. RELATION BETWEEN LENGTH OF INTRUSION AND DEPTH OF AQUIFER WHEN $Q_p = 1\,m^3$/DAY/m. WIDTH.

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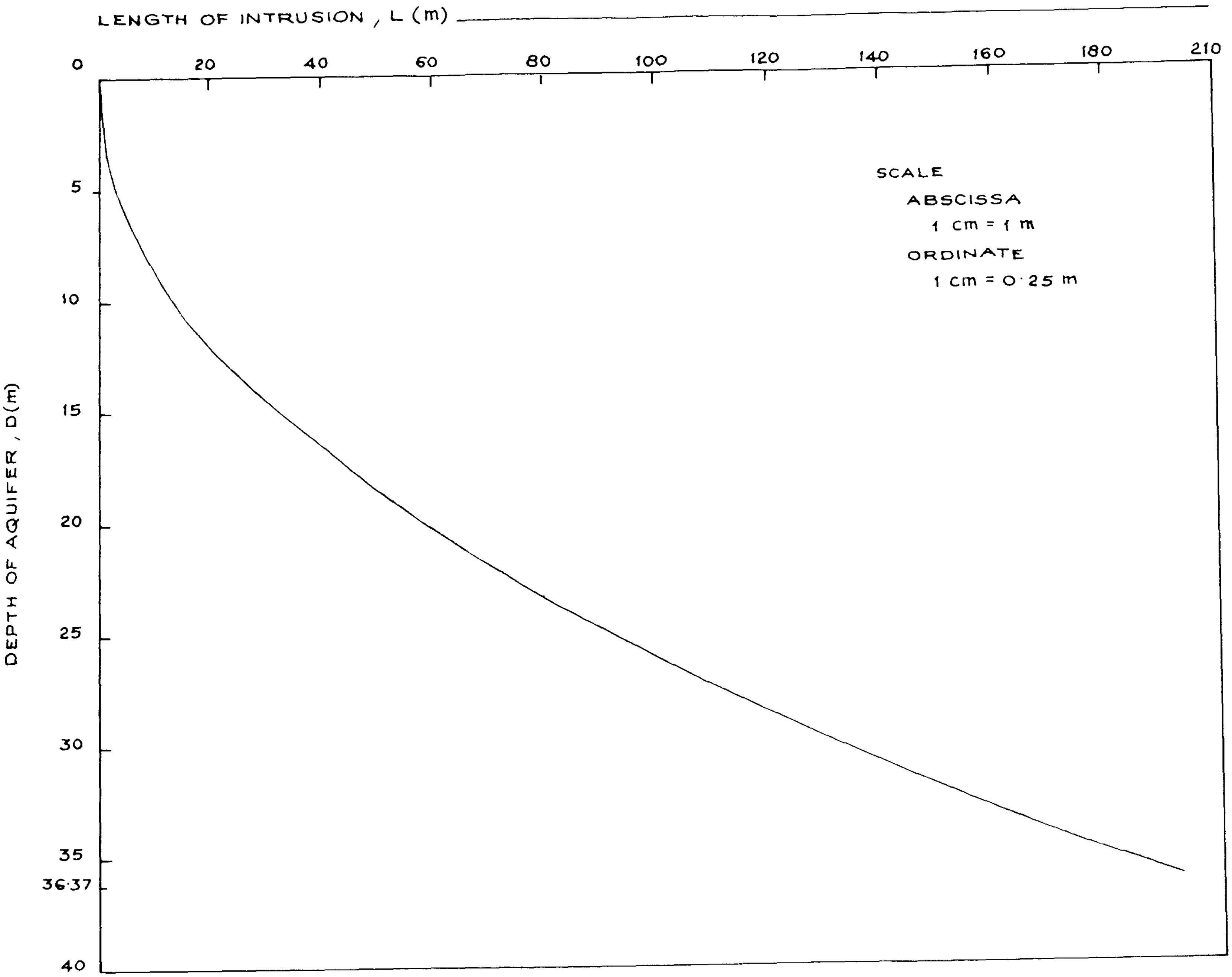

FIG.4.17.RELATION BETWEEN LENGTH OF INTRUSION AND DEPTH OF AQUIFER WHEN $Q_p = 2\ m^2$/DAY/m. WIDTH.

Table 4.18. Estimation of length of intrusion for various aquifer depth when $Q_p = 4 m^3$/day/metre width

Depth (m)	Length of intrusion (m)
5	3.4
10	16.0
15	37.01
20	66.43
25	104.25
30	150.48
35	205.11
36.37	221.50

Table 4.19. Estimation of length of intrusion for various aquifer depth when $Q_p = 6\ m^3$/day/metre width

Depth (m)	Length of intrusion (m)
5	4.26
10	19.08
15	43.80
20	78.40
25	122.89
30	177.26
35	241.52
36.37	260.86

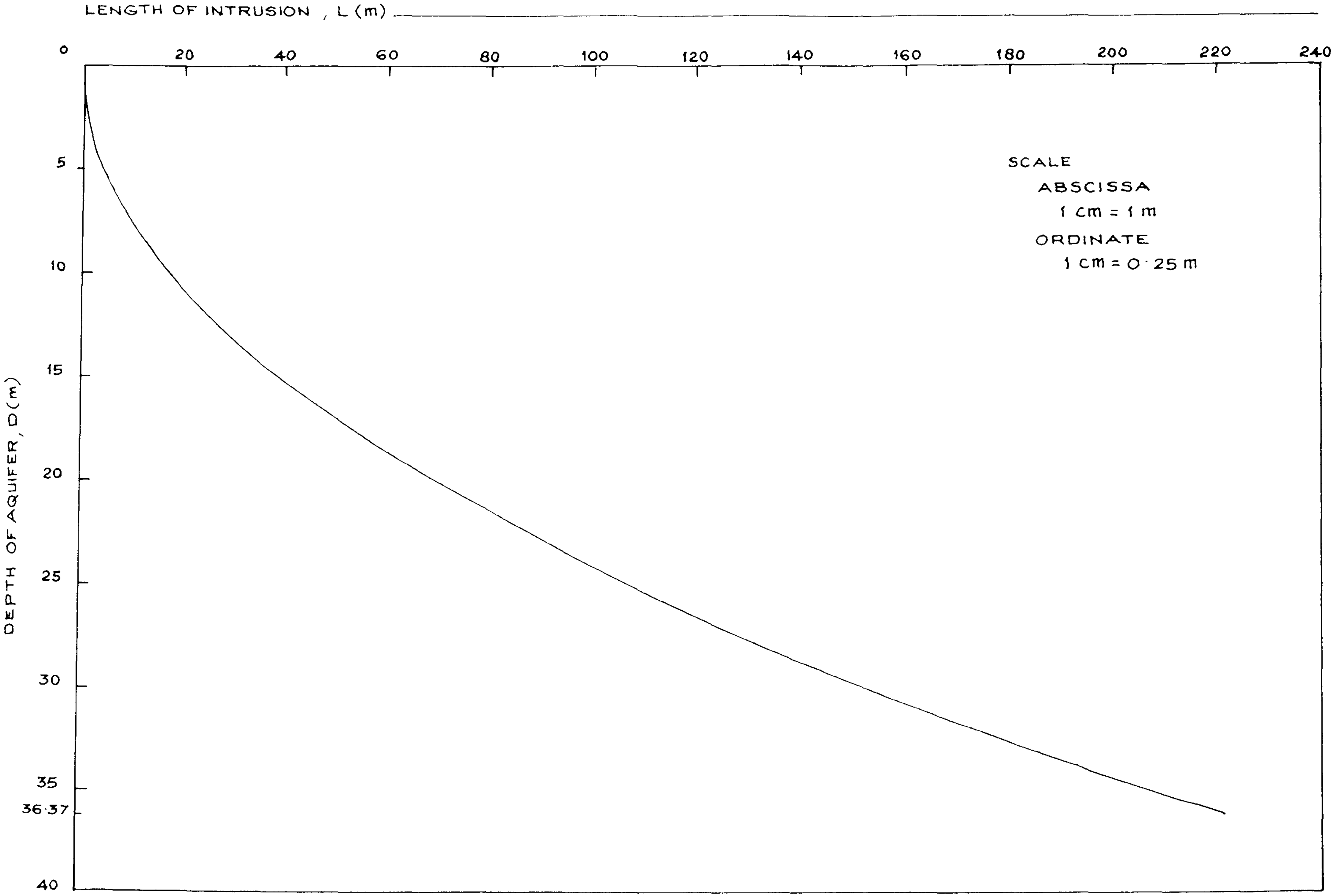

FIG.4·18. RELATION BETWEEN LENGTH OF INTRUSION AND DEPTH OF AQUIFER WHEN $Q_p = 4 m^3$/DAY/m. WIDTH.

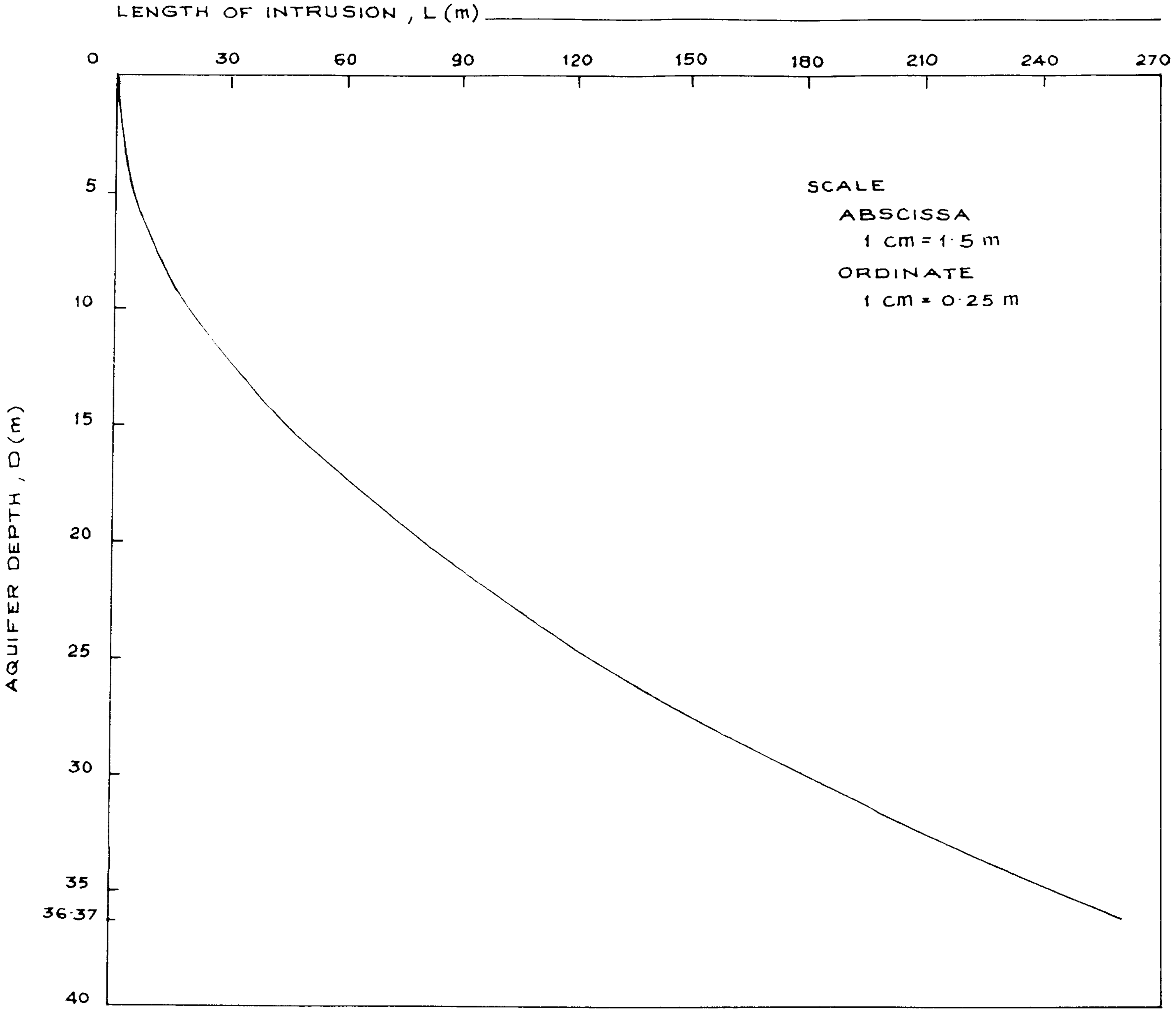

FIG.4.19 RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 6 m^3/DAY/m$ WIDTH AT TALIKULAM.

Table 4.20. Estimation of length of intrusion for various aquifer depth when Q_p = 8 m^3/day/metre width

Depth (m)	Length of intrusion (m)
5	5.4
10	23.34
15	53.23
20	95.08
25	148.89
30	214.65
35	292.37
36.37	315.75

Table 4.21 Estimation of length of intrusion for various aquifer depth when Q_p = 10 m^3/day/metre width

Depth (m)	Length of intrusion (m)
5	7.11
10	29.78
15	67.58
20	120.50
25	188.53
30	271.69
35	370.00
36.37	399.50

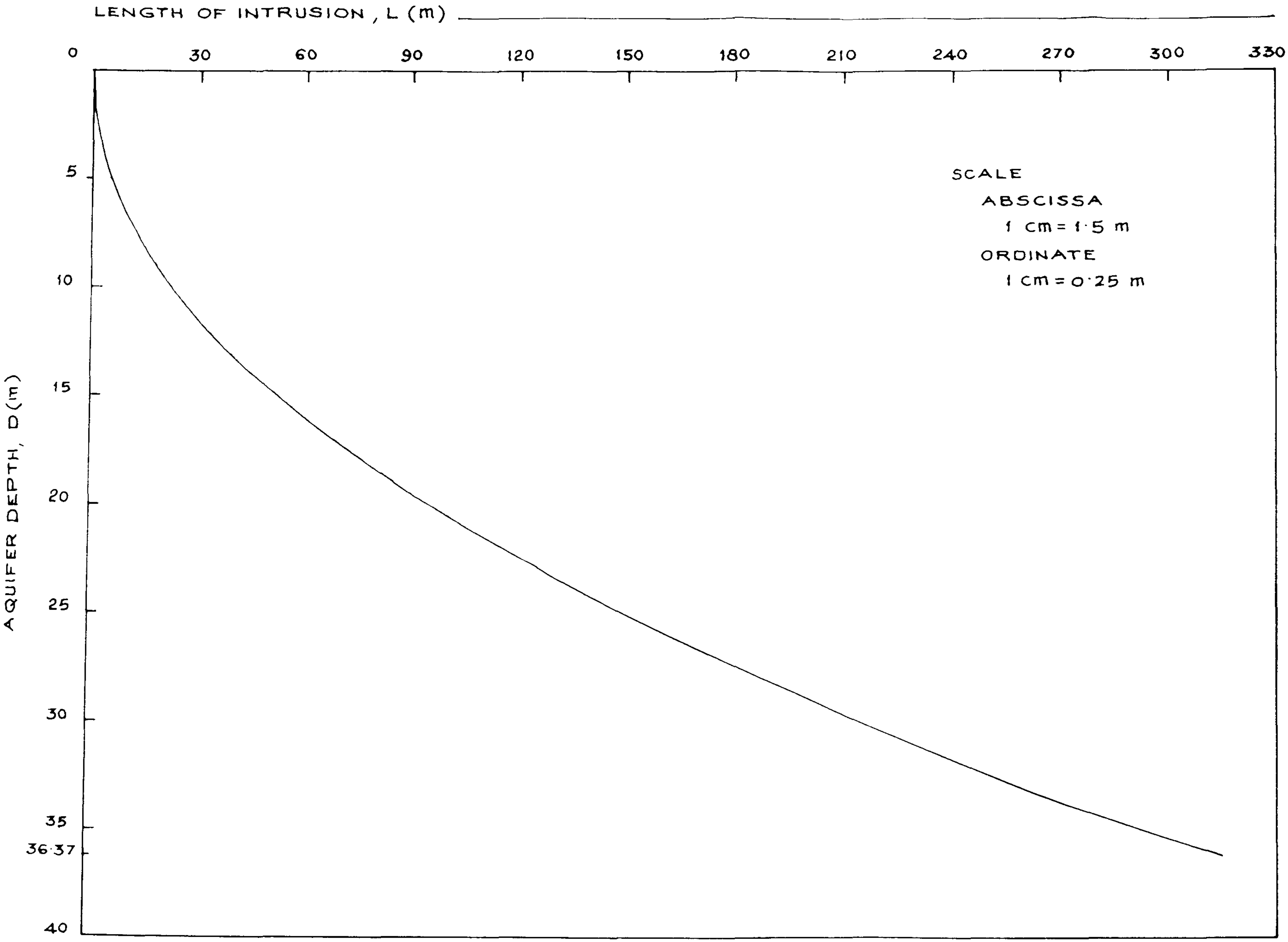

FIG.4.20 RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 8\ m^3/DAY/m$ WIDTH

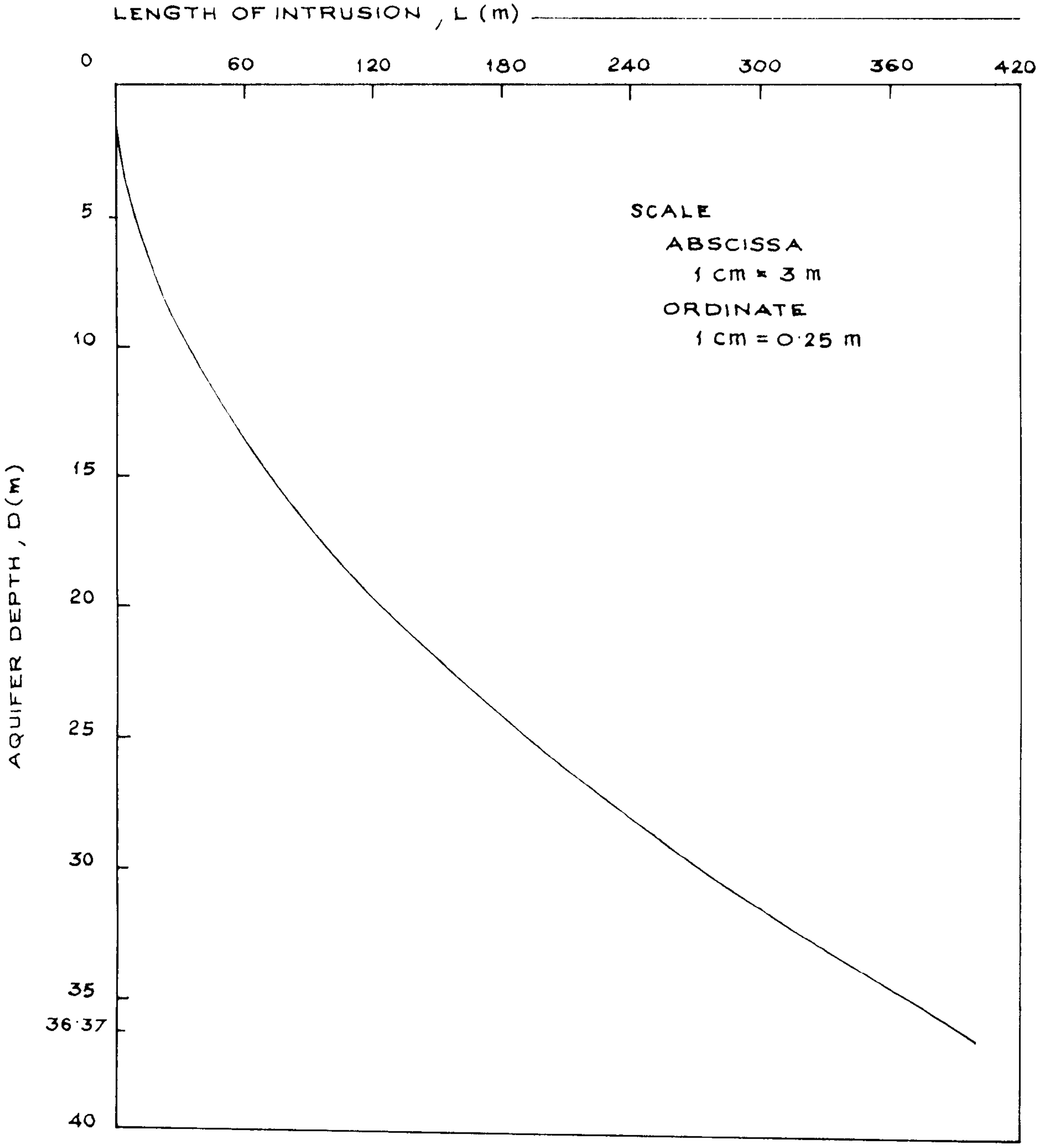

FIG.4.21. RELATION BETWEEN LENGTH OF INTRUSION AQUIFER DEPTH WHEN $Q_p = 10 m^3$/DAY/m. WIDTH. AT TALIKULAM.

Table 4.22. Estimation of length of intrusion for various aquifer depth when Q_p = 12 m^3/day/metre width

Depth (m)	Length of intrusion (m)
5	10.0
10	40.88
15	92.38
20	164.50
25	257.2
30	370.52
35	504.43
36.37	544.72

Table 4.23. Estimation of length of intrusion for various aquifer depth when Q_p = 14m^3/day/metre width

Depth (m)	Length of intrusion (m)
5	15.9
10	64.2
15	144.62
20	257.27
25	402.10
30	579.12
35	788.32
36.37	851.26

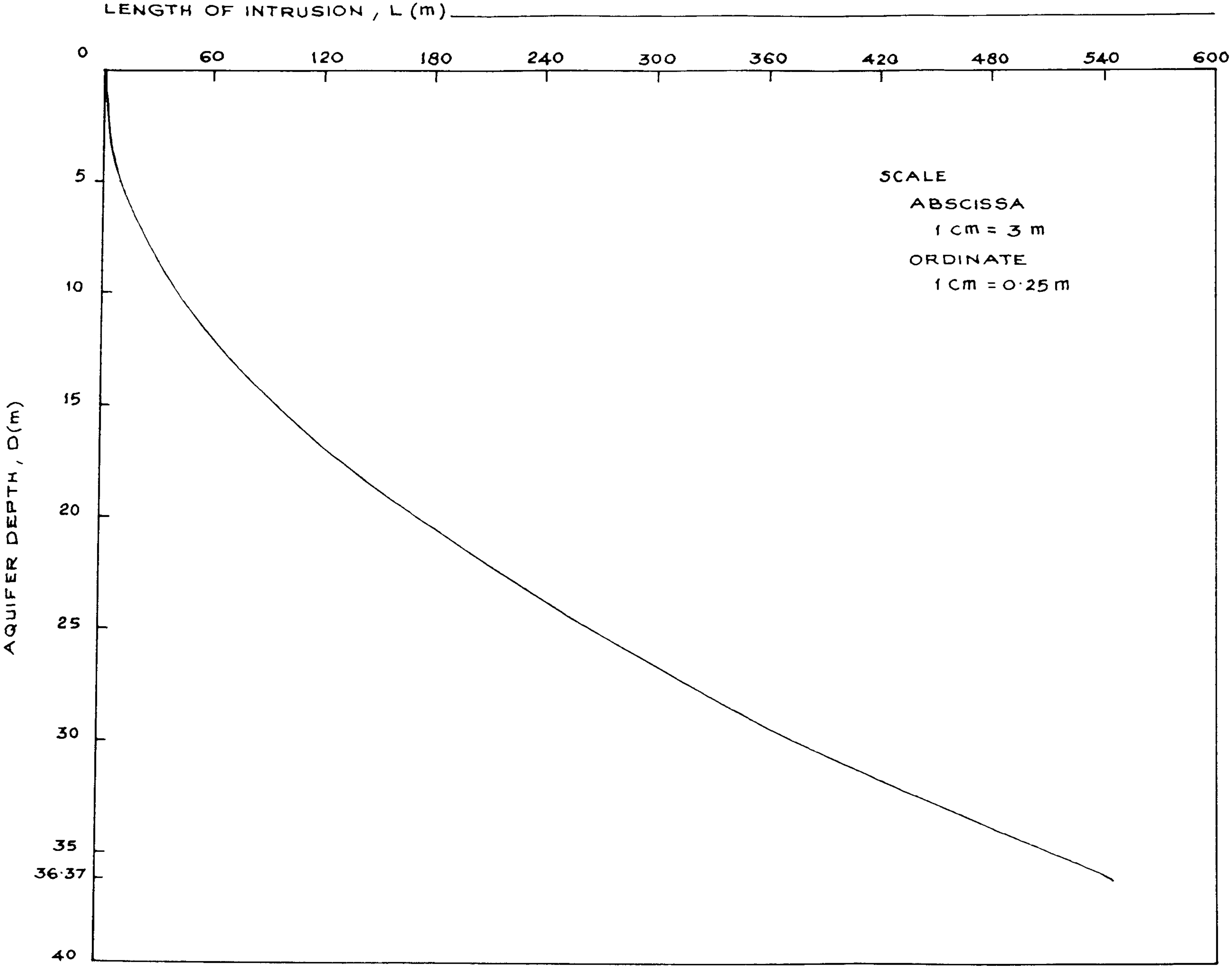

FIG.4·22 RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 12\ m^2/DAY/m$ WIDTH

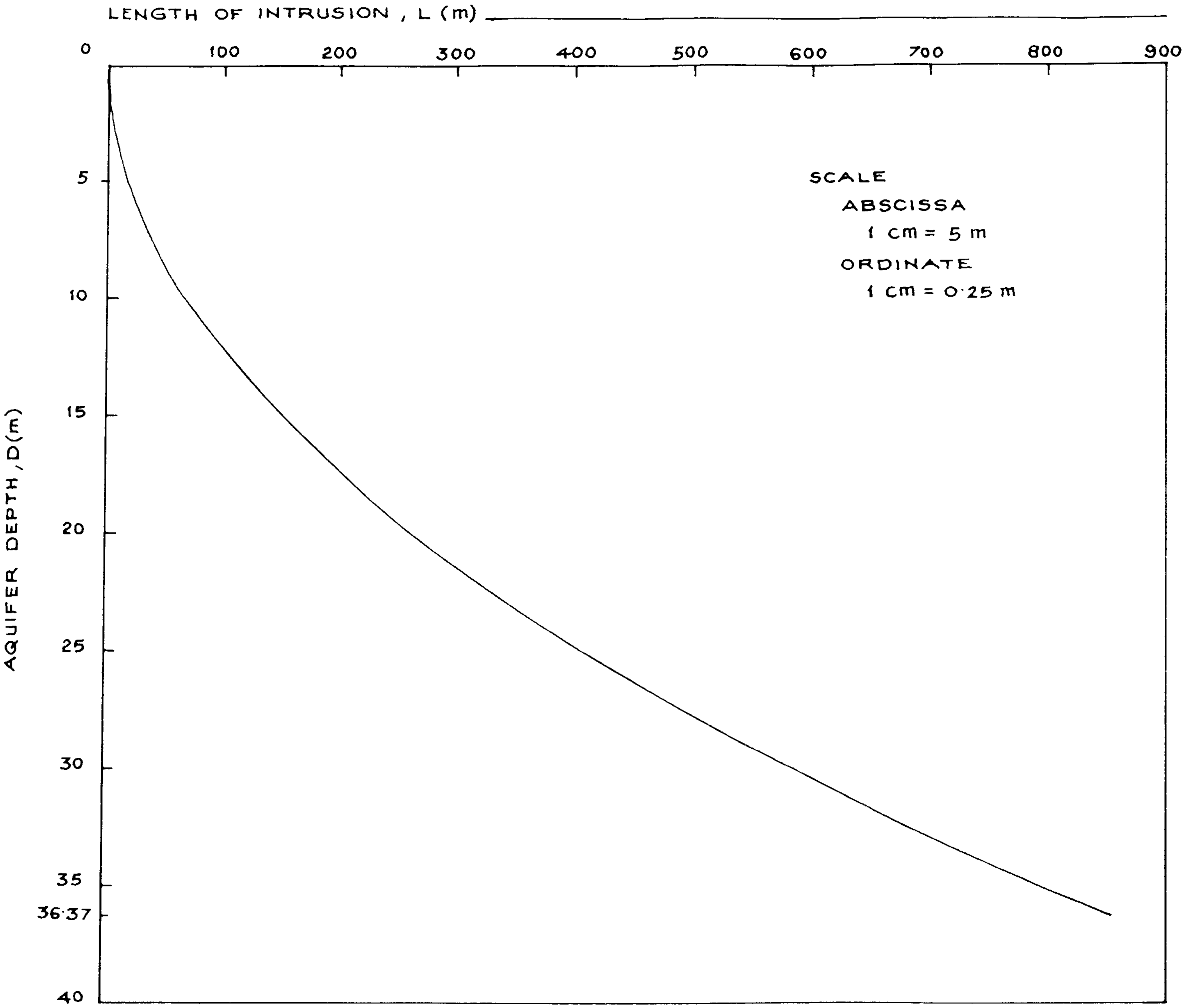

FIG.4·23. RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 14\,m^3/DAY/m$ WIDTH. AT TALIKULAM.

Table 4.24. **Advancement of saltwater wedge with increased groundwater exploitation**

Depth (m)	Q = QI	Q = 3/4QI	Q = 2/3QI	Q = QI/2	Q = QI/4
5	2.18	3.55	4.18	6.00	12.75
10	11.87	16.56	18.82	25.50	51.79
15	28.01	38.25	43.21	58.03	116.8
20	50.61	68.60	77.37	103.57	208.0
25	79.67	107.64	121.28	162.12	325.0
30	115.19	155.34	175.0	233.68	468.17
35	157.16	211.72	238.38	318.25	637.30
36.37	171.06	228.69	257.46	343.69	688.21

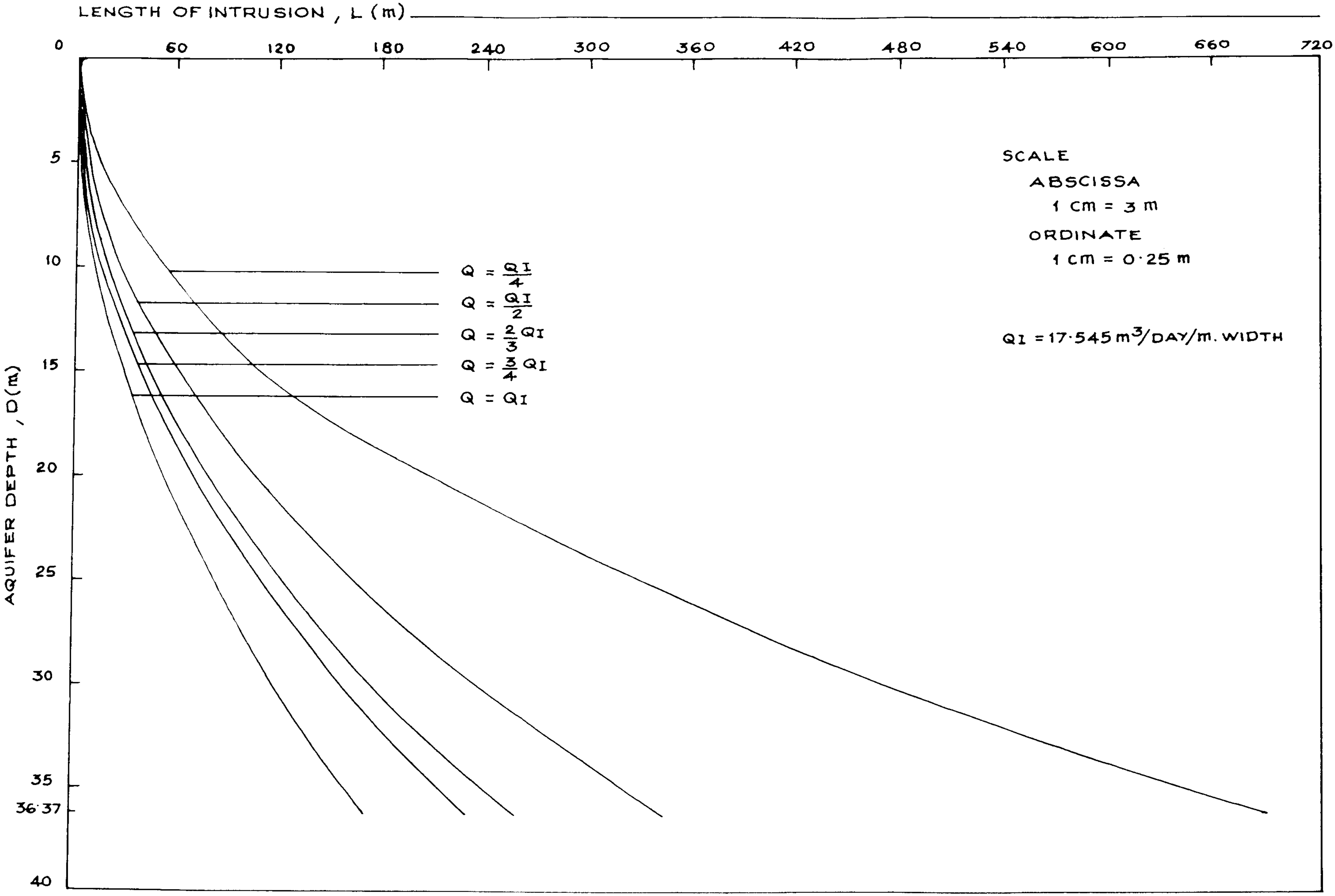

FIG.4·24.GRAPH SHOWING THE ADVANCEMENT OF SALT WATER WEDGE WITH INCREASED GROUND WATER EXPLOITATION. AT PALIKULAM.

level, there would be a chance for salinity intrusion. Hence no further pumping for agricultural purposes is recommended.

4.3 Site at Kazhimbram

Basic observations

From the bore hole data given in Appendix III, the depth of the aquifer was found to be 24m. Distance of selected wells from the shore were 245.76 m, 354.9 m and 386.1 m respectively. The coefficient of permeability was calculated as 119.78 m/day. Figure 3.6 shows the measured values of height of fresh water.

4.3.1 Aquifer discharge (QI)

The aquifer discharge at the time of the observation was calculated as 3.91 m^3/day/metre width of coast line. The length of intrusion corresponding to the aquifer discharge was found to be 225.73 m. Figure 4.25 shows the length of intrusion when the aquifer discharge is 3.91 m^3/day/metre width of coast line. The selected wells were situated at a distance of 245.76 m, 354.9 m and 386.1 m from the shore. So the wells were located beyond the above length of intrusion. Therefore there was no sea water intrusion at the time of observation.

Table 4.26 gives the water analysis results. The water samples were analysed for pH, EC, Ca^{++}, Mg^{++}, and Na^{+} contents. It was found

Table 4.25. Estimation of length of intrusion for various aquifer depth when Ql = 3.91 m^3/day/metre width

Depth (m)	Length of intrusion (m)
3	3.2
6	13.78
9	31.40
12	56.20
15	88.0
18	126.80
21	172.74
24	225.73

Table 4.26. Chemical analysis of water

Sl. No.	Source of water	Sodium Adsorption Ratio	pH	Electrical conductivity (µmhos/cm)	Calcium m.eq/litre	Magnesium m.eq/litre	Calcium + Magnesium m. eq/litre	Sodium m.eq/litre
1	Well No. 1	1.099	7.3	300	1.175	0.4095	2.1845	1.148
2	Well No. 2	1.573	7.35	400	1.56	0.16575	1.72575	1.461
3	Well No. 3	1.42476	6.7	500	1.95	0.273	2.223	1.496

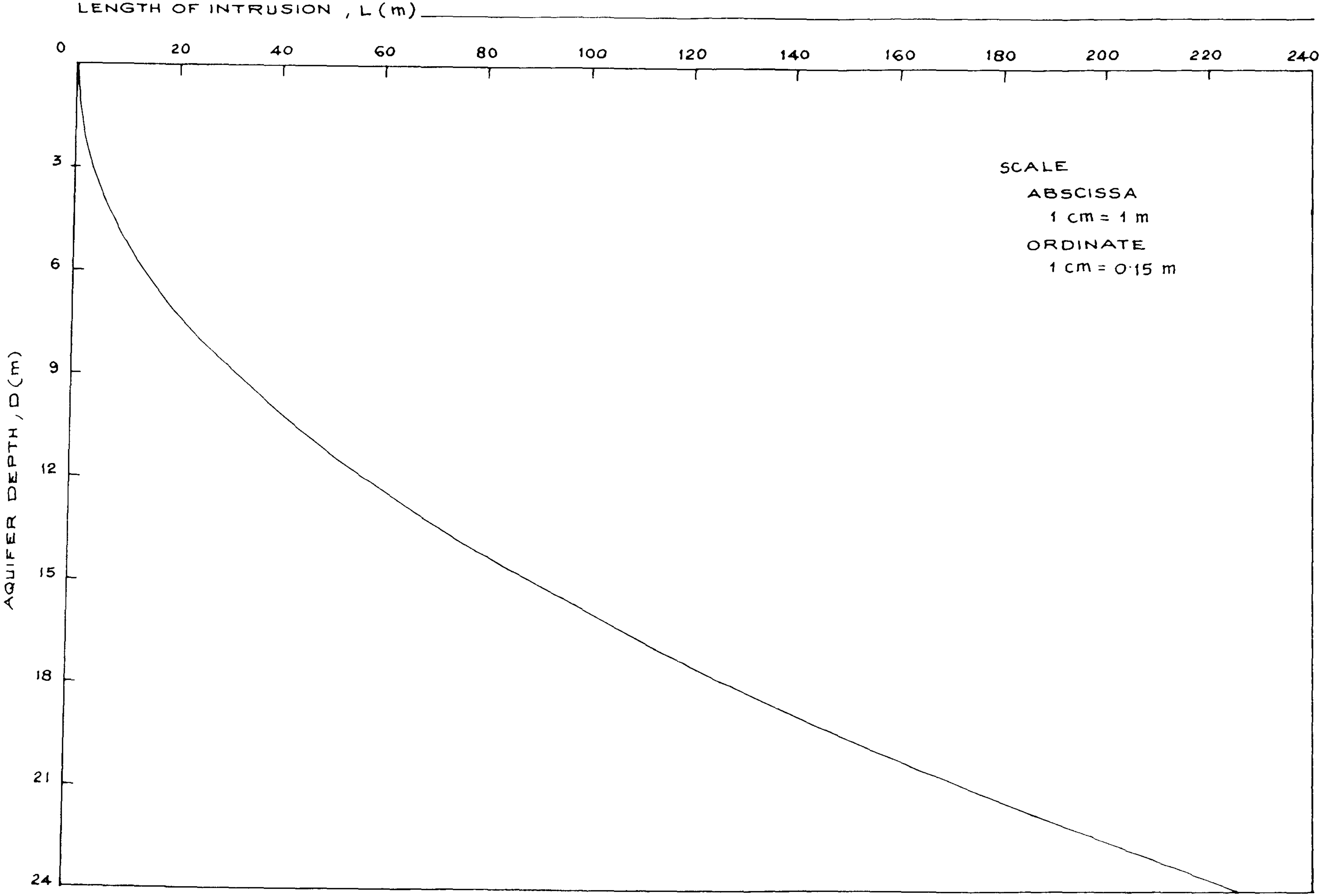

FIG.4.25 GRAPH SHOWING THE POSITION OF INTERFACE WHEN $Q_I = 3{\cdot}91 m^3$/DAY/m WIDTH AT [illegible]

that pH values varied from 6.7 to 7.35, EC varied between 300 to 500 µmhos/cm and SAR varied from 1.56 to 1.95. With reference to the classification of irrigation waters, the water samples come under C_2 - S_1 class. So the quality of water is good.

Therefore there was no salinity intrusion problem beyond 225.73 m from the shore.

4.3.2 Maximum pumping rate (Q_p)

Maximum pumping rate of fresh water for various depth of wells were calculated with the help of a computer programme. Table 4.27 gives the maximum pumping rate of fresh water at a distance of 245.76 m, 354.9 m and 386.1 m respectively. The positions of the interface for length of intrusions of 245.76m, 354.9 m and 386.1 m are shown in Figs. 4.26, 4.27 and 4.28. The length of intrusion for various pumping rates were calculated and are given in Table 4.27. Figure 4.29 shows the pumping rates of various length of intrusions. Figures 4.30 to 4.35 show the length of intrusion when the pumping rates are 0.2 m^3/day/metre width, 0.5 m^3/day/metre width, 1 m^3/day/metre width, 1.5 m^3/day/metre width, 2 m^3/day/metre width, 2.5 m^3/day/metre width and 3 m^3/day/metre width respectively. Using these graphs, the depth of the wells could be fixed without causing the problem of salinity.

Table 4.27. Computation of maximum pumping rate for various distances from the coast

Depth (m)	Maximum pumping rate (m^3/day/metre width)		
	X = 245.76 m	X = 354.9 m	X = 386.1 m
1	3.9037614	3.9056065	3.9059582
2	3.8850451	3.8926017	3.8940077
3	3.8537633	3.8709857	3.8741491
4	3.8100917	3.8407586	3.8463821
5	3.7538550	3.8019199	3.8105311
6	3.6852283	3.7542944	3.7669475
7	3.6040366	3.6980574	3.7151043
8	3.5103669	3.6332092	3.6555283
9	3.4042199	3.5597498	3.5880442
10	3.2856832	3.4775035	3.5124757
11	3.1545811	3.3868217	3.4289992
12	3.0110891	3.2873528	3.33376143
13	2.855032	3.1792724	3.2383213
14	2.6865849	3.0625811	3.1309440
15	2.5056605	2.9372783	3.0158341
16	2.3122585	2.8031886	2.8926404
17	2.1064668	2.6606634	2.7615380
18	1.8881974	2.5093510	2.6225276
19	1.6575384	2.3496032	2.4756088
20	1.4144018	2.1810684	2.320606
21	1.1588757	2.0039222	2.1578708
22	0.89087176	1.8181648	1.9868754
23	0.61056638	1.6237962	1.8083234
24	0.31778312	1.4206407	1.6216874

Table 4.28. Position of different length of intrusion for various aquifer depth

Depth (m)	Length of intrusion (m)		
	L_1 = 245.76	L_2 = 354.9	L_3 = 386.1
3	3.5	5.3	5.8
6	15.1	22.0	24.0
9	34.3	49.7	54.1
12	61.2	88.5	96.3
15	95.9	138.5	150.6
18	138.2	199.5	217.0
21	188.2	271.6	295.3
24	245.76	354.9	386.1

Table 4.29. Computation of length of intrusion for various pumping rate

Maximum pumping rate (m^3/day/metre width)	Length of intrusion (m)
3	971.32
2.5	626.81
2.0	462.64
1.5	366.58
1.0	303.51
0.5	258.93
0.2	238.00

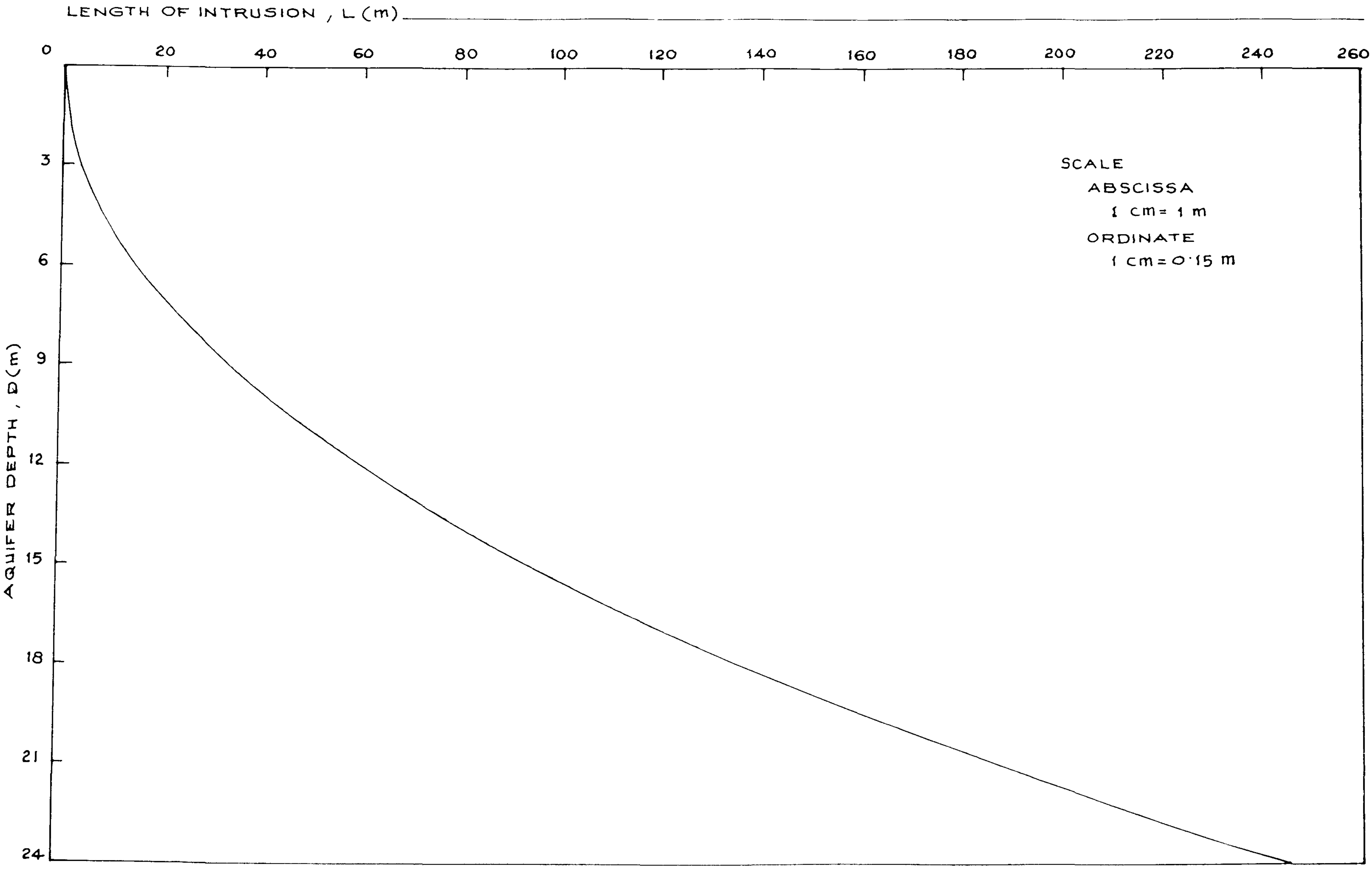

FIG.4·26. GRAPH SHOWING THE POSITION OF INTERFACE WHEN X = 245·76 m. [illegible]

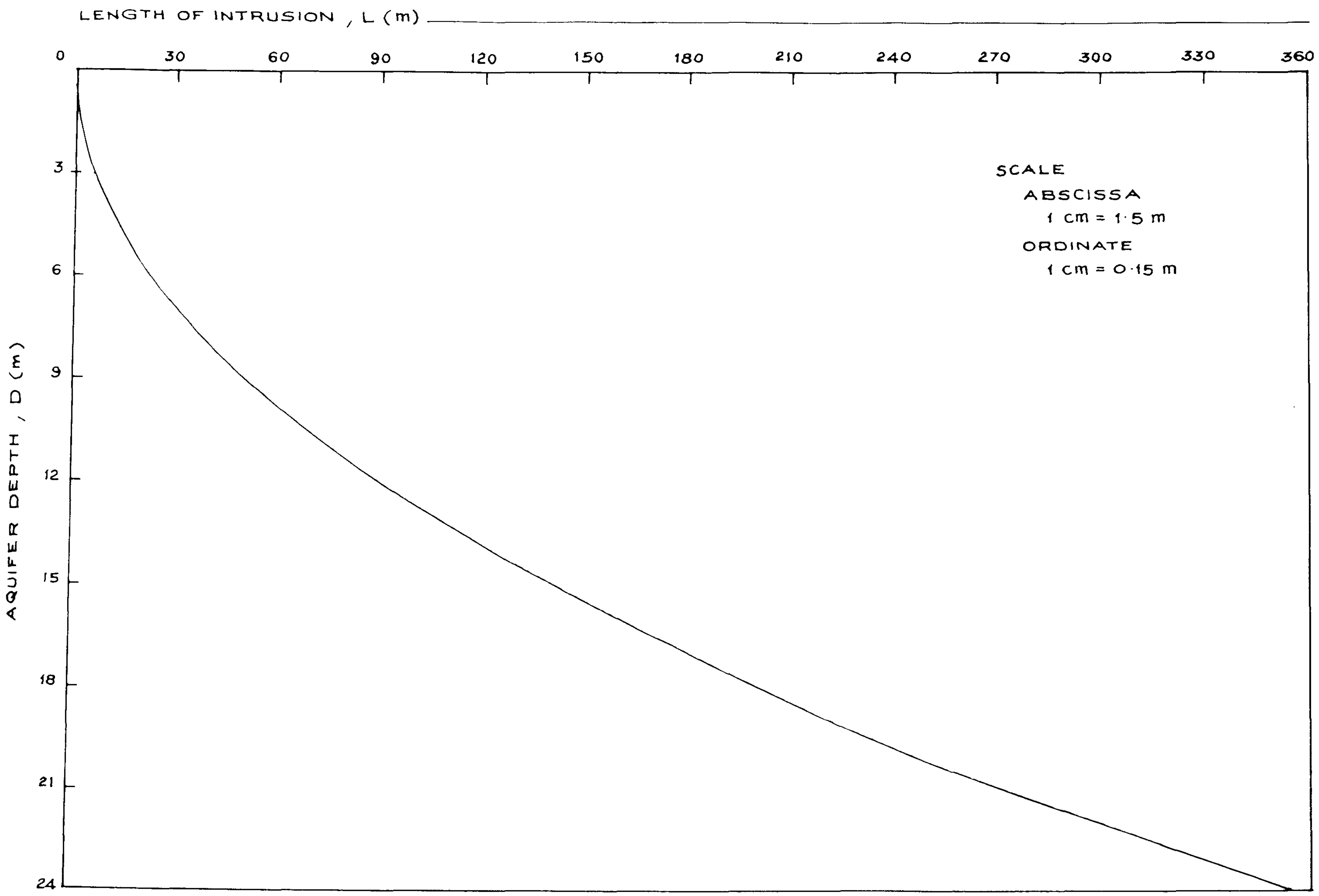

FIG. 4·27. GRAPH SHOWING THE POSITION OF INTERFACE WHEN x = 354·9 m [illegible]

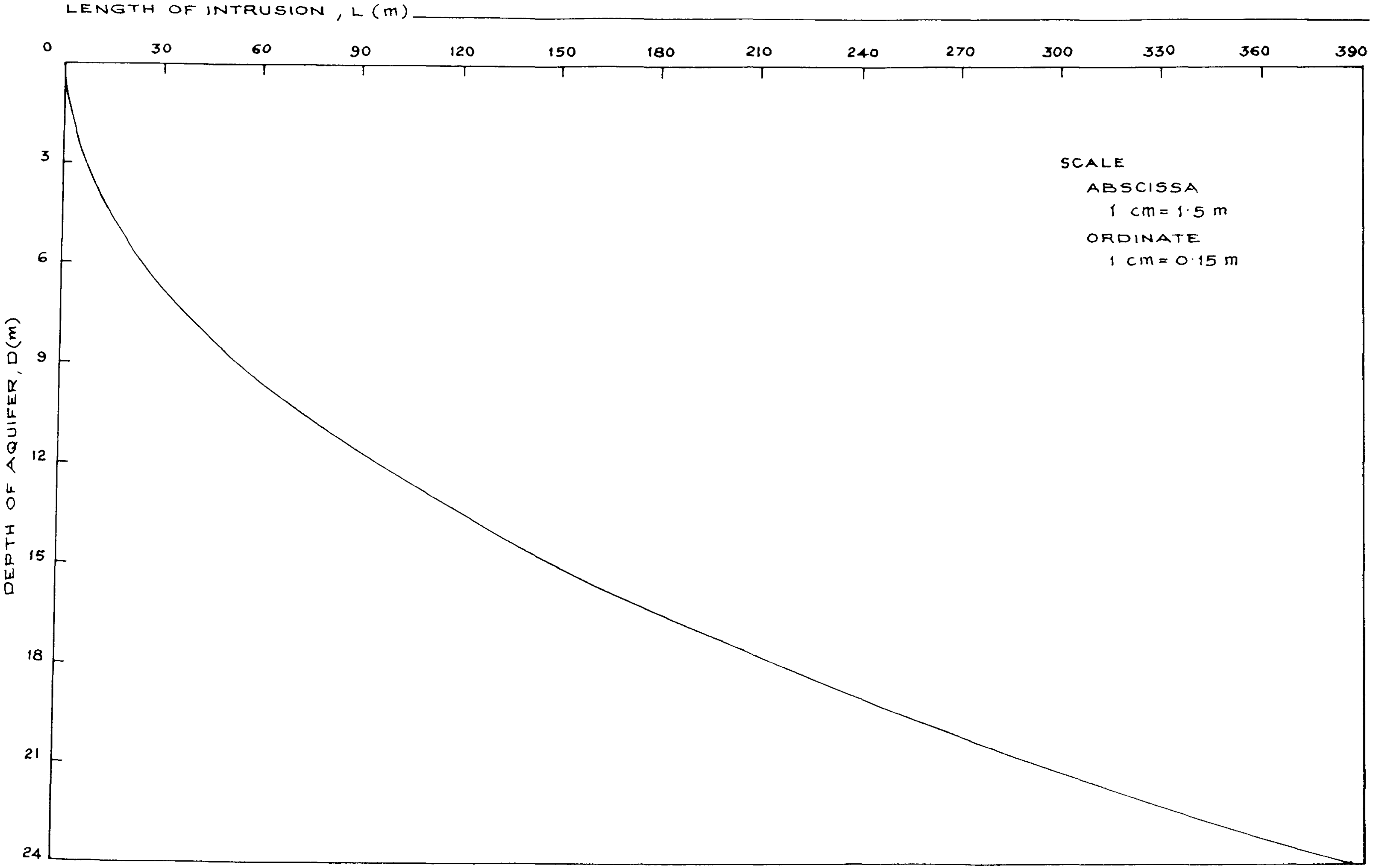

FIG.4.28. GRAPH SHOWING THE POSITION OF INTERFACE WHEN X = 386·1 m. AT KAZHIMBRAM.

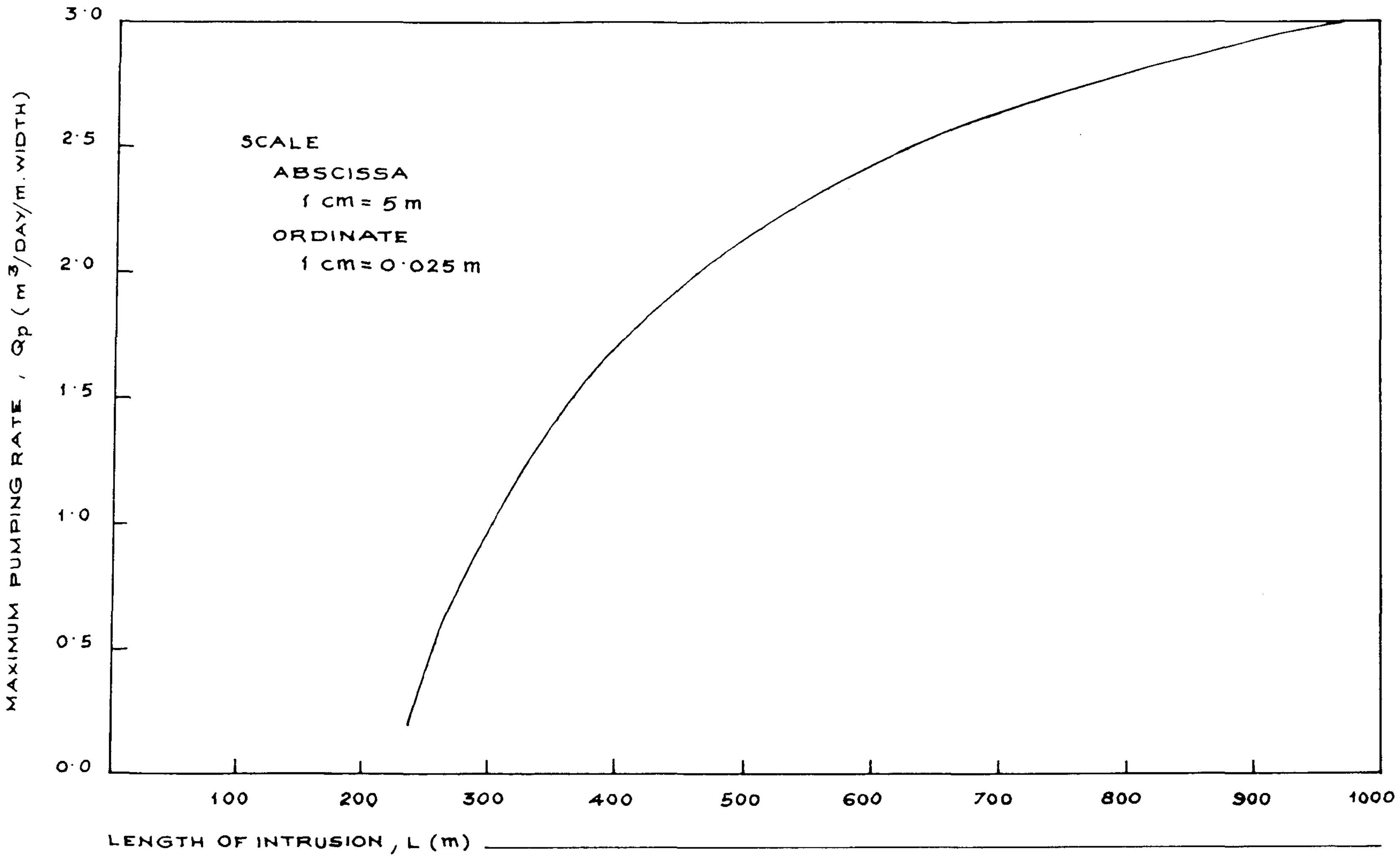

FIG.4·29.GRAPH SHOWING THE RELATION BETWEEN LENGTH OF INTRUSION AND MAXIMUM PUMPING RATE.
AT KAZHIMBRAM.

Table 4.30 Estimation of length of intrusion for various aquifer depth when Q_p = 0.2 m^3/day/metre width

Depth (m)	Length of intrusion (m)
3	3.4
6	14.4
9	33.2
12	58.70
15	92.70
18	132.50
21	182.10
24	238.0

Table 4.31. Estimation of length of intrusion for various aquifer depth when Q_p = 0.5 m^3/day/metre width

Depth (m)	Length of intrusion (m)
3	3.7
6	16.0
9	36.2
12	64.5
15	101.0
18	145.5
21	198.2
24	259.0

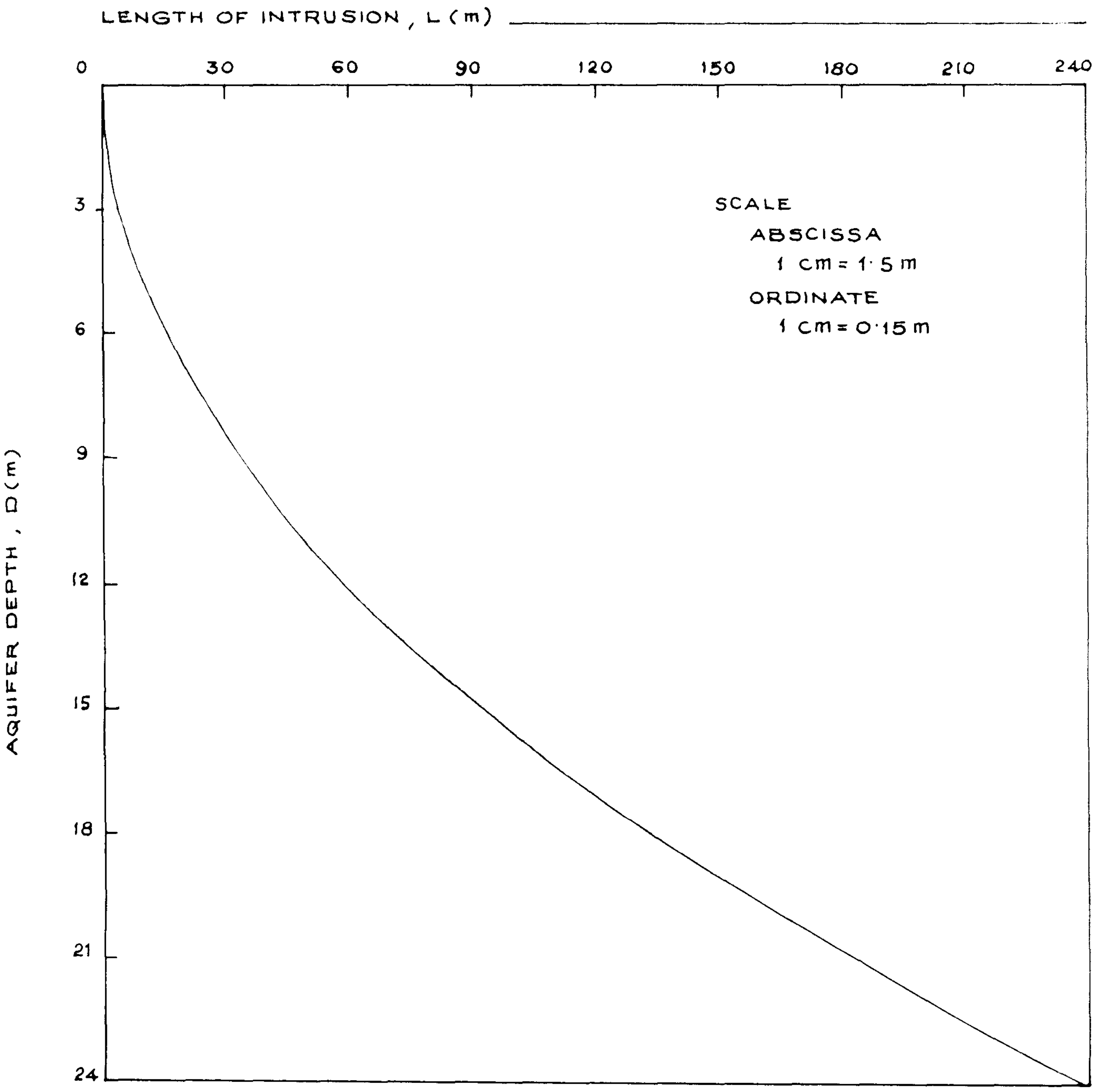

FIG. 4·30. GRAPH SHOWING THE RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 0{\cdot}2\,m^3$/DAY/m. WIDTH. AT KAZHIMBRA

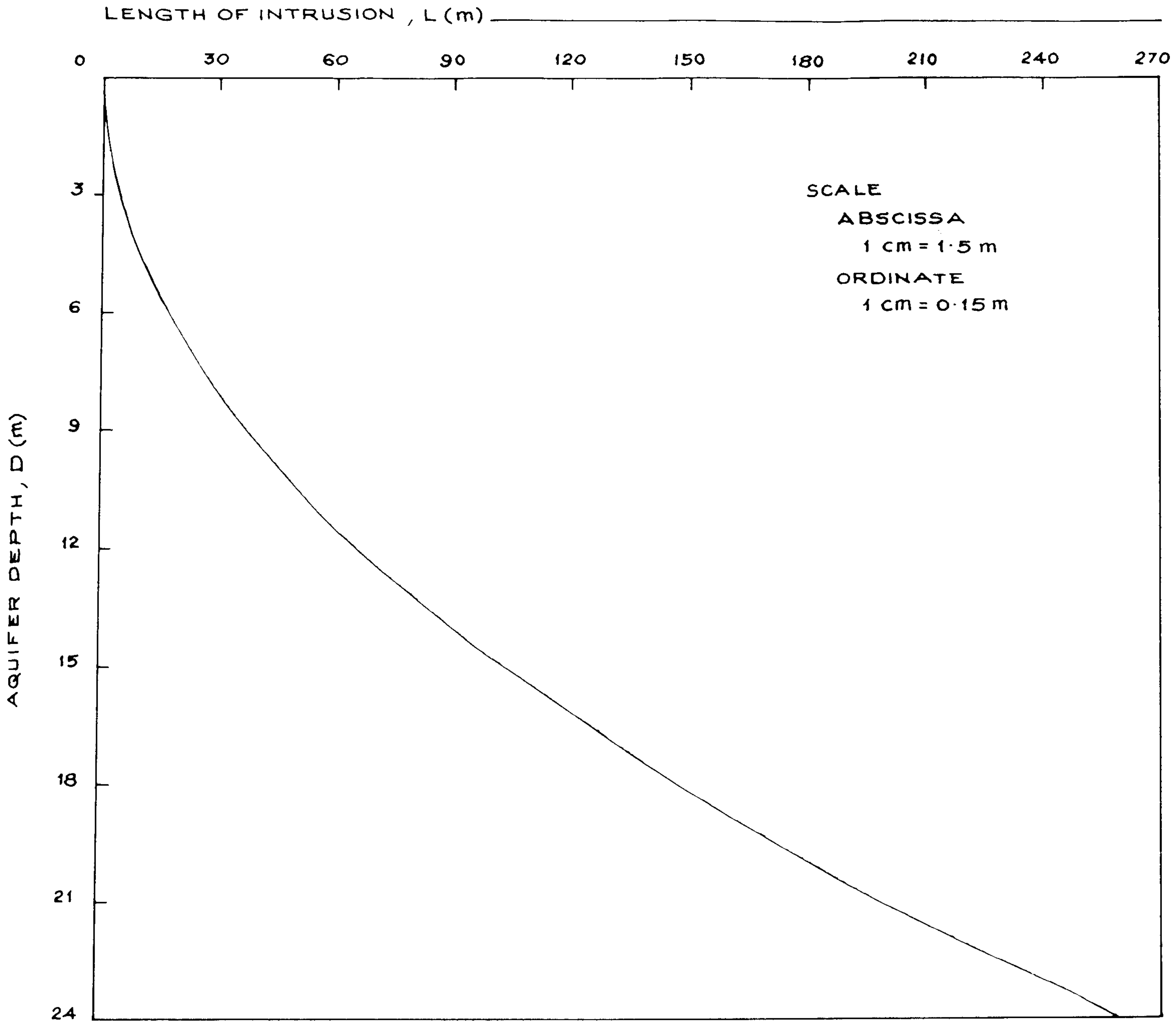

FIG.4.31. RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPH WHEN $Q_p = 0{\cdot}5\,m^3$/DAY/m.WIDTH.

[illegible]

Table 4.32. Estimation of length of intrusion for various aquifer depth when Q_p = 1 m^3/day/metre width

Depth (m)	Length of intrusion (m)
3	4.5
6	18.5
9	42.5
12	75.0
15	118.0
18	169.1
21	232.3
24	300.8

Table 4.33 Estimation of length of intrusion for various aquifer depth when Q_p = 1.5 m^3/day/metre width

Depth (m)	Length of intrusion (m)
3	5.5
6	22.7
9	51.4
12	91.3
15	143.1
18	205.7
21	280.6
24	365.8

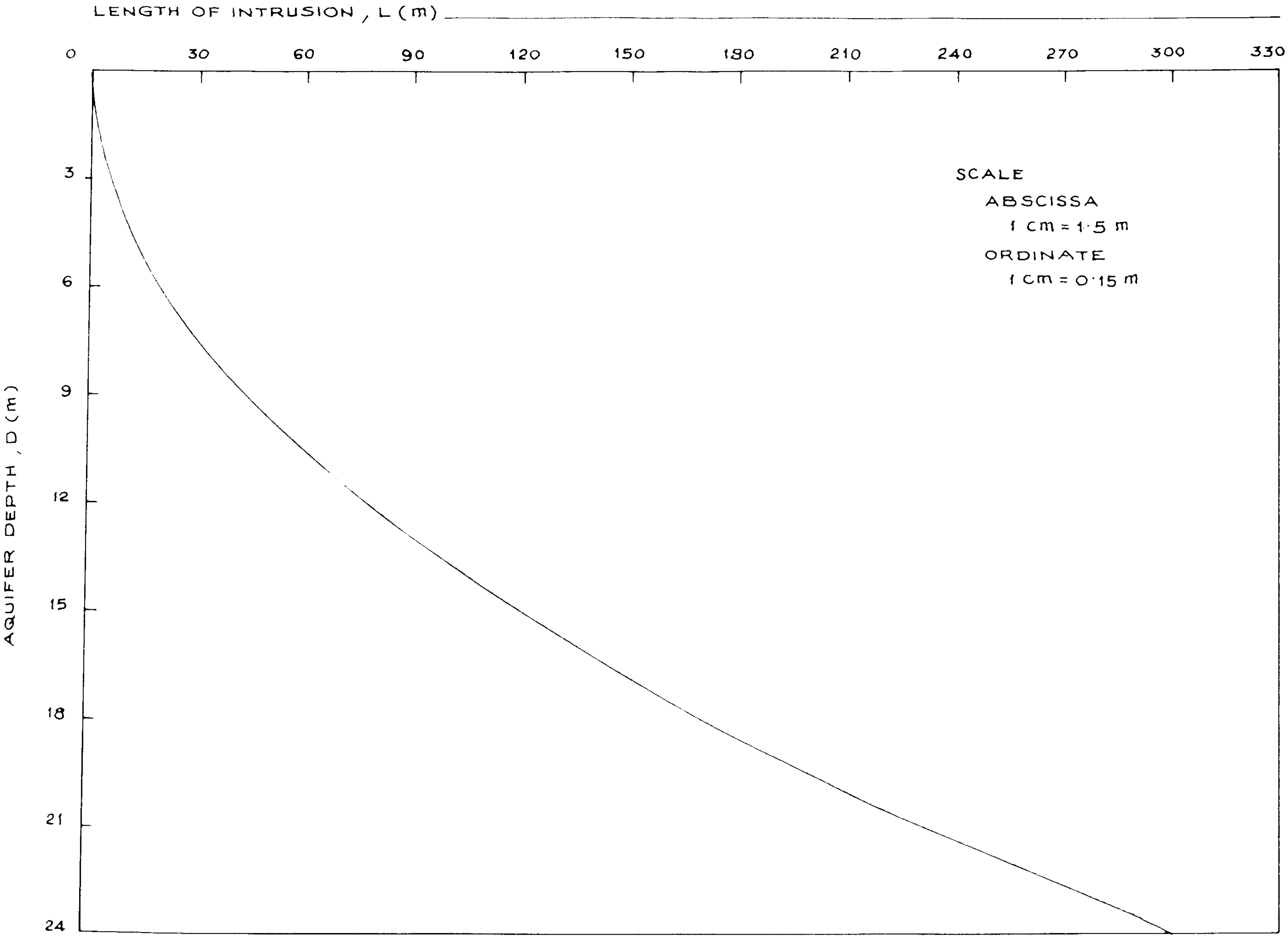

FIG. 4.32. RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 1 m^3$/DAY/m.WIDTH AT KAZHIMPRAM

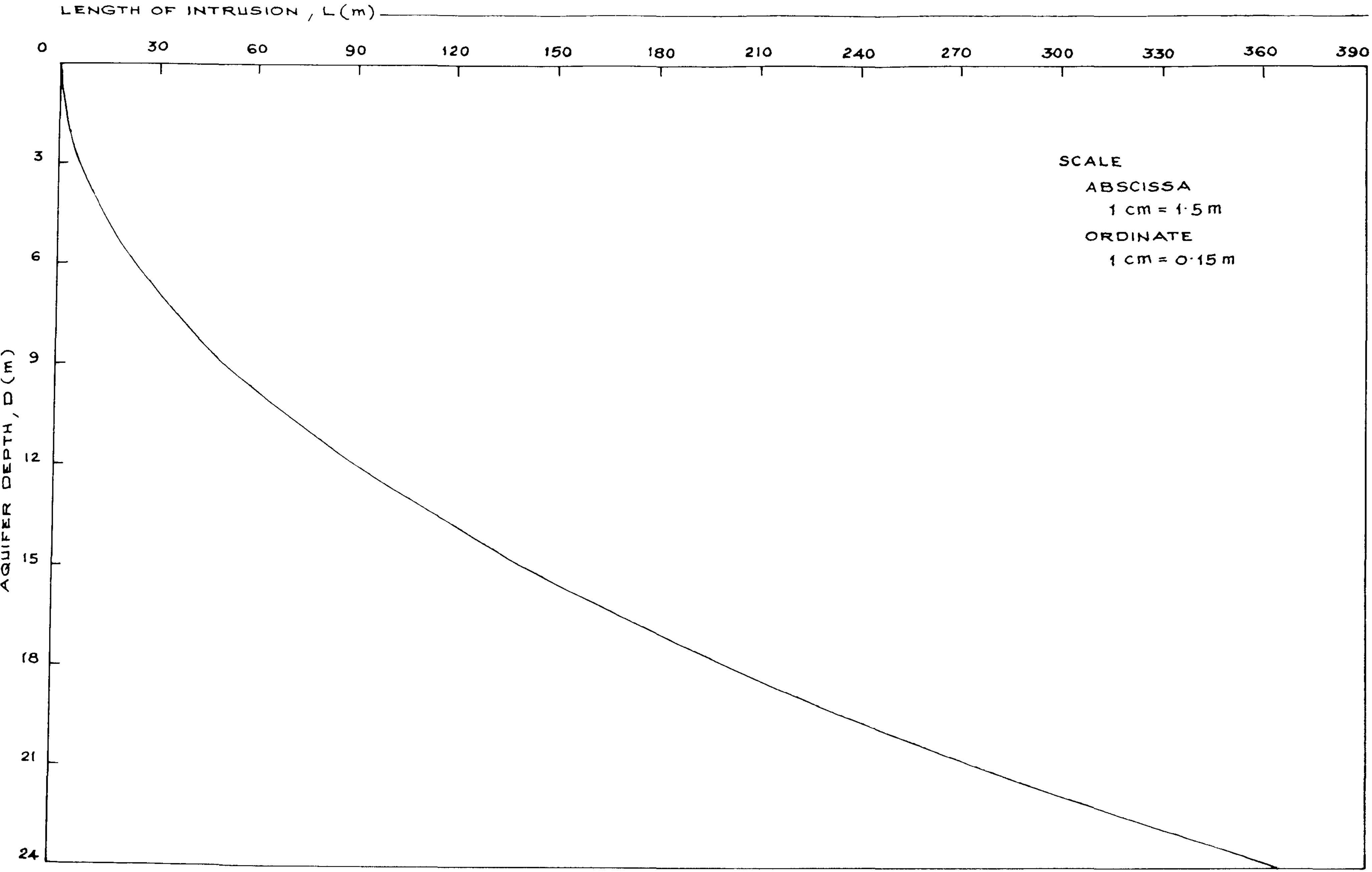

FIG.4.33.RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 1{\cdot}5\ m^3$/DAY/m. WIDTH.

Table 4.34. Estimation of length of intrusion for various aquifer depth when $Q_p = 2\ m^3$/day/metre width

Depth (m)	Length of intrusion (m)
3	7.1
6	28.6
9	65.0
12	115.0
15	180.6
18	258.8
21	354.2
24	462.6

Table 4.35. Estimation of length of intrusion for various aquifer depth when $Q_p = 2.5\ m^3$/day/metre width

Depth (m)	Length of intrusion (m)
3	9.7
6	39.0
9	88.0
12	156.6
15	244.8
18	352.5
21	479.9
24	626.8

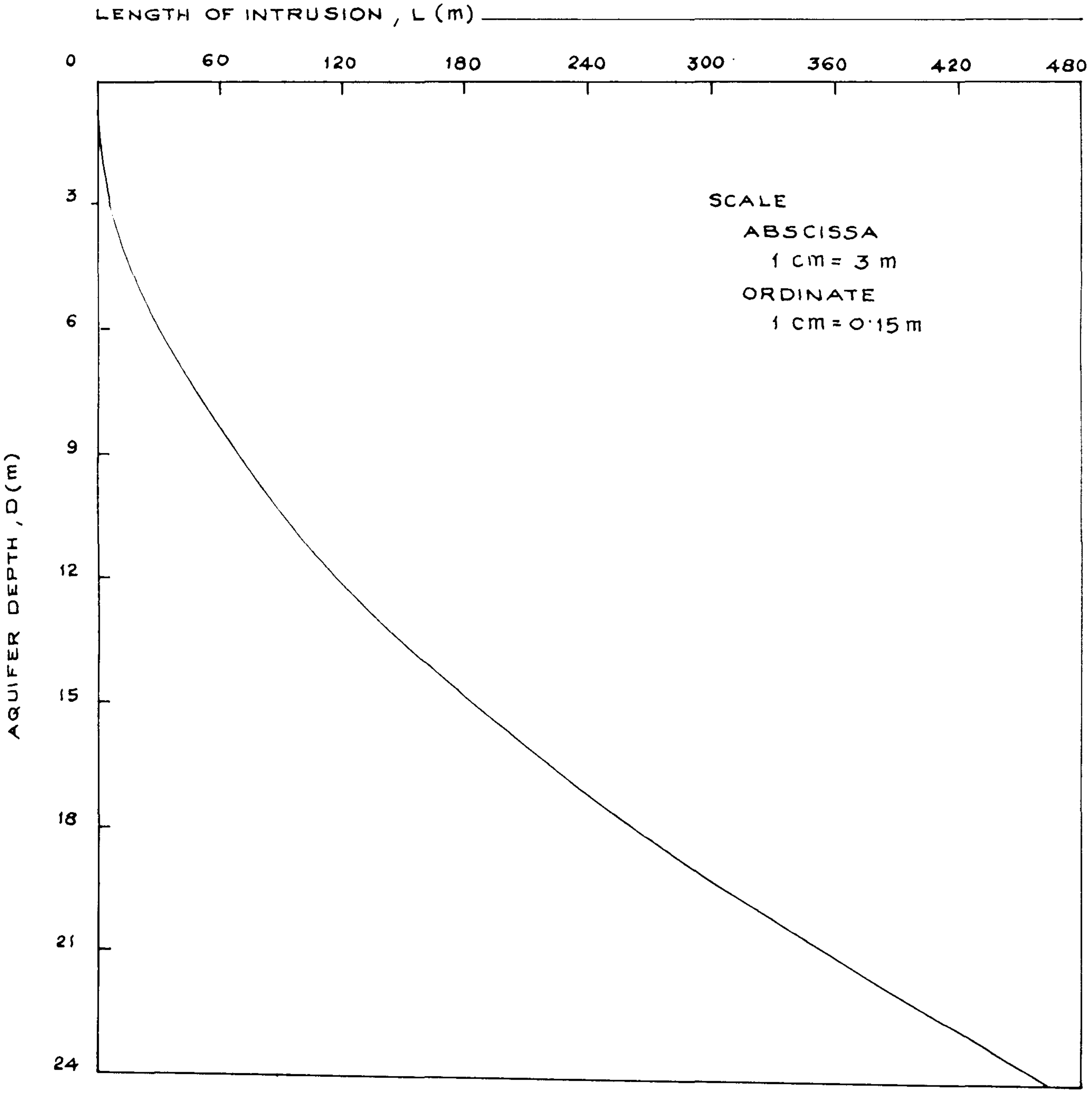

FIG. 4·34. RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 2\ m^3$/DAY/m. WIDTH. AT KAZHIMBRAM.

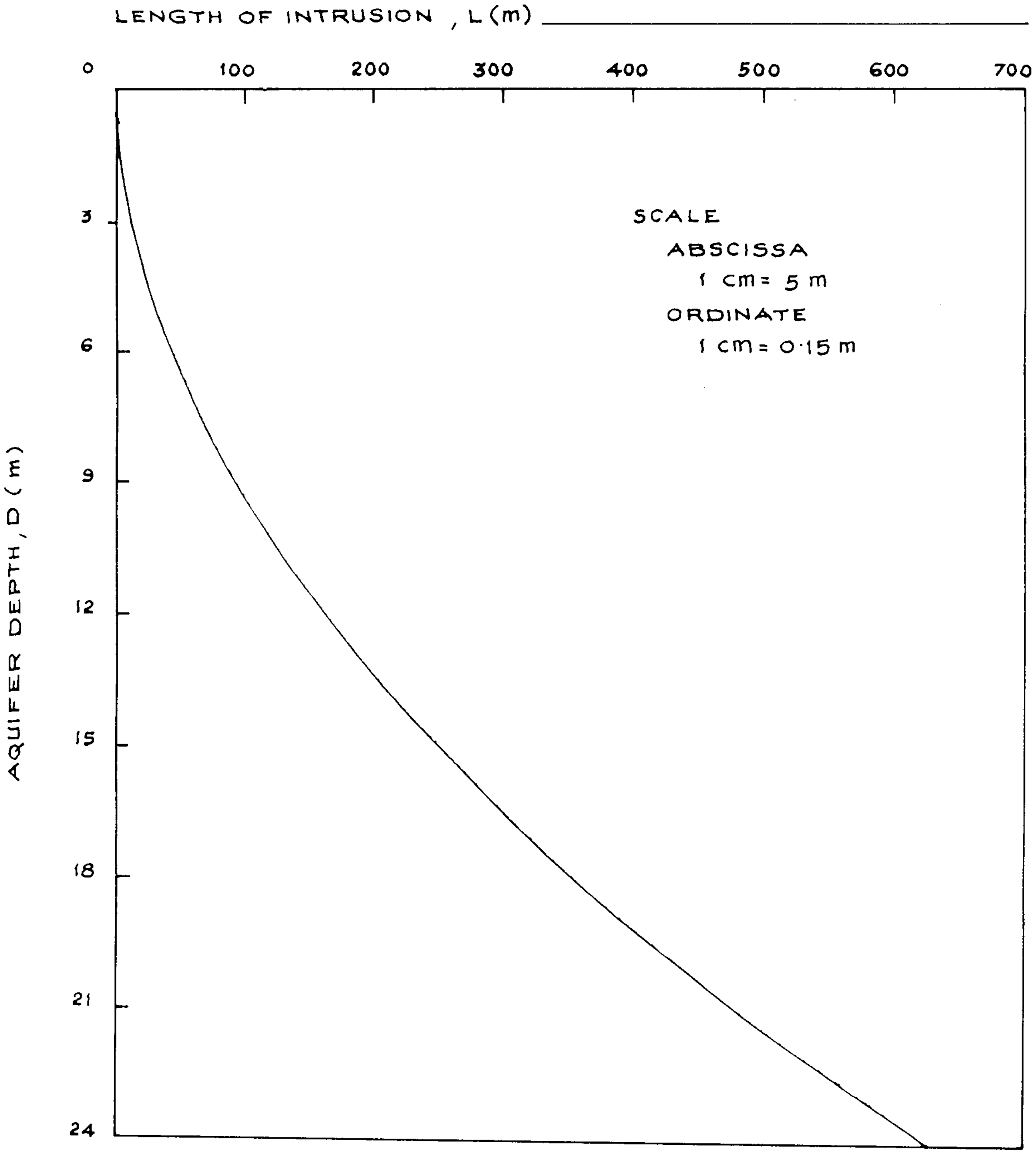

FIG.4·35. RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 2{\cdot}5\ m^3$/DAY/m.WIDTH. AT KAZHIMBRAM.

Table 4.36. Estimation of length of intrusion for various aquifer depth when Q_p = 3 m^3/day/metre width

Depth (m)	Length of intrusion (m)
3	15.1
6	60.6
9	136.5
12	242.7
15	379.4
18	546.2
21	743.6
24	971.3

Table 4.37. Advancement of saltwater wedge with increased groundwater exploitation

Depth (m)	Length of intrusion (m)				
	Q = QI	Q = 3/4QI	Q = 2/3QI	Q = QI/2	Q = QI/4
3	3.2	4.45	5.1	6.9	14.0
6	13.78	18.6	20.8	28.1	56.4
9	31.40	42.1	47.4	63.4	127.1
12	56.20	75.0	83.9	112.9	225.7
15	88.0	117.5	132.1	176.5	353.2
18	126.8	169.1	189.1	254.2	508.0
21	172.74	230.5	259.1	346.0	692.3
24	225.73	300.8	336.3	452.1	903.23

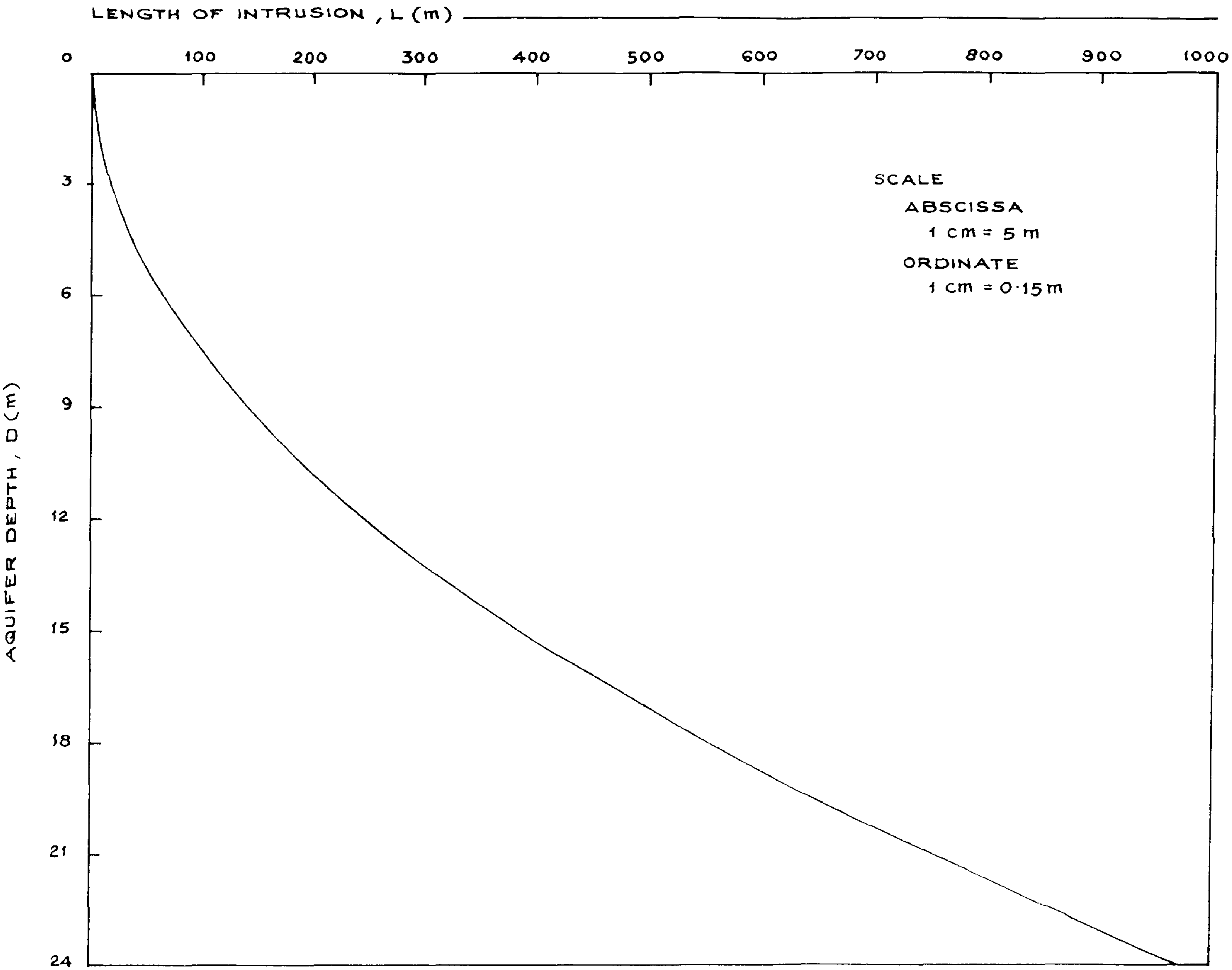

FIG. 4.36 RELATION BETWEEN LENGTH OF INTRUSION AND AQUIFER DEPTH WHEN $Q_p = 3 m^3/DAY/m$ WIDTH AT KAZHIMBRAM

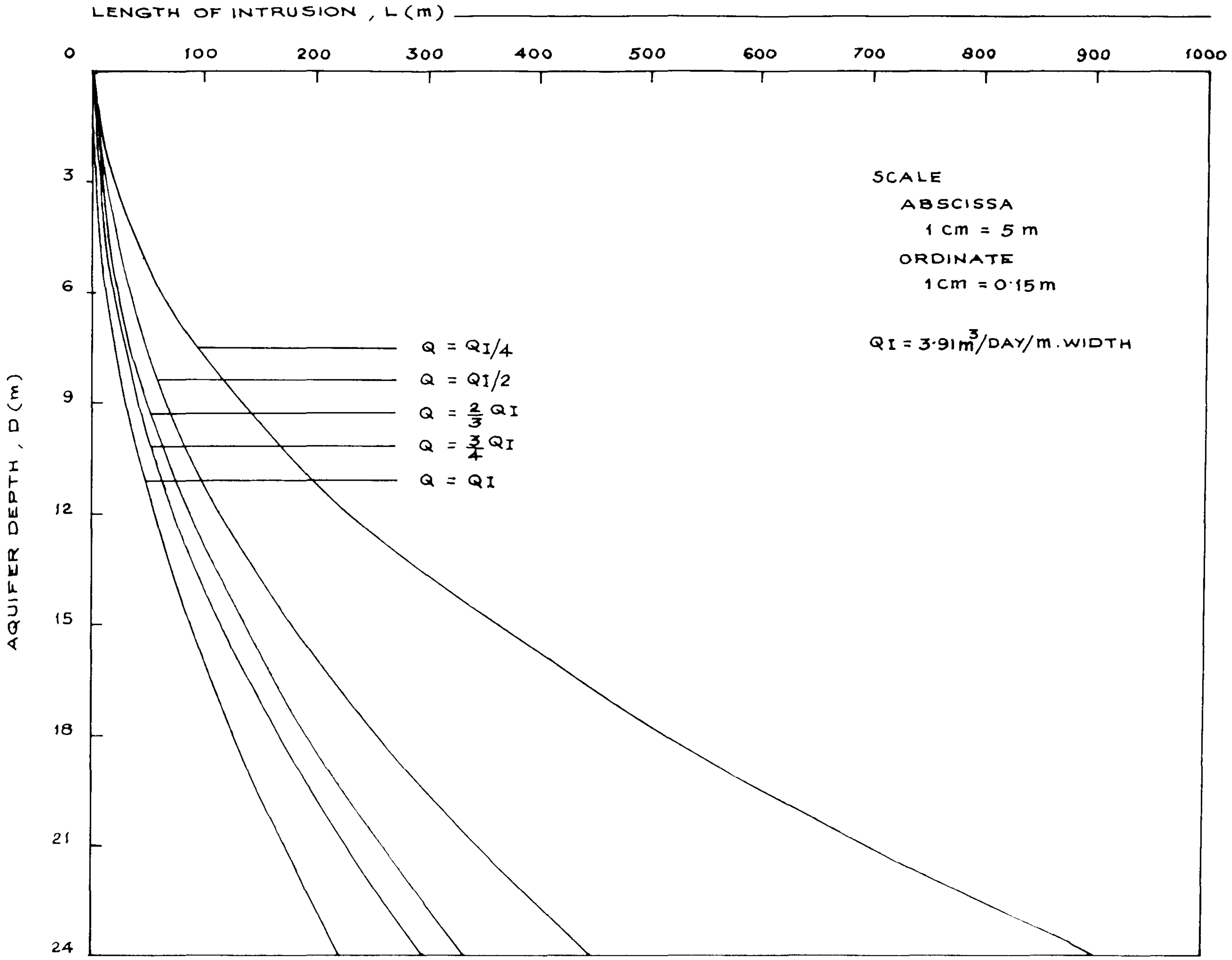

FIG 4·37 GRAPH SHOWING THE ADVANCEMENT OF SALT WATER WEDGE WITH INCREASED GROUND WATER EXPLOITATION AT KAZHIMBRAM.

4.3.3 Advancement of saltwater wedge with increased ground water exploitation

The advancement of saltwater wedge with increased groundwater exploitation is shown in Fig. 4.37. If the aquifer discharge reduces to two-third of the present aquifer discharge, the interface comes nearer to the second selected well. When reduced to half and one-fourth of the present discharge, the interface goes beyond the selected wells. Therefore there is a change of salinity intrusion if the aquifer discharge is reduced beyond the present aquifer discharge. Hence there is only limited scope for further pumping.

The result of the studies are summarised in Table 4.38. Fresh water could be pumped from each well at a depth upto bottom of aquifer of each site.

Table 4.38. Comparative study of results

Sl. No.	Details	Site		
		Nattika	Talikulam	Edamuttam
1.	Depth of aquifer from mean sea level (D)	8.81 m	36.37 m	24.0 m
2.	Permeability coefficient (k)	120.92 m/day	178.17 m/day	119.78 m/day
3.	Fresh water discharge (Ql)	3.14 m^3/day/m	17.545 m^3/day/m	3.91 m^3/day/m
4.	Length of intrusion (L)	38.02 m	171.06 m	225.73 m
5.	Well location from coast line			
	Well 1	188.59 m	178.40 m	245.76 m
	Well 2	260.93 m	283.78 m	354.90 m
	Well 3	348.53 m	362.79 m	386.10 m
6.	Permissible maximum pumping rate * (m^3/day/m)			
	Well 1	2.50	0.71	0.32
	Well 2	2.60	6.92	1.42
	Well 3	2.79	9.23	1.62

* Well depth upto bottom of aquifer

Summary

SUMMARY

The problem of contamination of surface and groundwater by the intrusion of salinity from the sea is very common in coastal areas. The present study was conducted on three villages in Trichur district namely Nattika, Talikulam and Edamuttam. Field observations were taken in the observation wells along the alignments normal to the coastline. The aquifer parameters for these sites were determined using the bore hole data for the sites.

The aquifer discharge of Nattika site was found to be 3.14 m^3/day/metre width of coastline. The length of intrusion corresponding to the aquifer discharge was 38.02m. The position of interface and the maximum rate of pumping of groundwater from the aquifer for various depths were determined using the equation of the interface. Distance of the selected wells from the shore were 188.59 m, 260.93 m and 348.53 m respectively. There was no salinity intrusion at this site because the selected wells were found to lie beyond the length of intrusion corresponding to the present aquifer discharge. The chemical analysis indicated that the water of this site was free from salt content.

17.545 m^3/day/metre width of coastline was the aquifer discharge of Talikulam site. 171.06 m was the length of intrusion corresponding to the aquifer discharge. The selected wells were 178.4m, 283.78m and 362.79 m away from the coastline. The wells were found to lie beyond the length of intrusion corresponding to the present aquifer

discharge. The water quality test showed that the quality of water was good. So there was no salinity intrusion at Tallikulam.

The aquifer discharge at Kazhimbram was 3.91 m^3/day/metre width of coastline. The length of intrusion corresponding to the aquifer discharge was 225.73 m. The selected wells were situated at a distance of 245.76m, 354.9m and 386.1 m respectively from the coast. There was no salinity intrusion because the chemical analysis did not show any sign of salt content and the wells were found to lie beyond the length of intrusion corresponding to the present aquifer discharge.

Advancement of saltwater wedge with increased groundwater exploitation showed that there would be a chance of salinity intrusion if the aquifer discharge is reduced from the present aquifer discharge. At Tallikulam when the aquifer discharge is reduced to one-fourth of the present aquifer discharge, the length of intrusion would be 688.21 m which is beyond the present selected wells. At Kazhimbram when the aquifer discharge is reduced to half and one-fourth of the present aquifer discharge, the interface is found beyond the selected wells. So there would be a chance of salinity intrusion at Tallikulam and Kazhimbram if the aquifer discharge is reduced from the present aquifer discharge.

The determination of interface positions for various pumping rates could be effectively used in fixing the location of wells. The result of the present study lead to a better understanding of the sea water intrusion problem and these could be made use of in the design and planning of groundwater systems in coastal areas for a better utilisation of the groundwater resources.

It was found that limited quantity of ground water storage is available in Nattika, Talikulam and Kazhimbram areas. The design of groundwater systems requires further studies such as :

1. Quantitative estimation of groundwater flow for various months of the year
2. Assessment of groundwater storage for different seasons
3. Groundwater utilisation pattern
4. Average annual rainfall
5. Mean annual maximum and minimum temperature
6. Frequency of pumping and pumping schedule.

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Appendices

Appendix I. Lithology of Nattika site

Lithology	Depth range (m)	Thickness (m)
Sand, fine to medium grained	0 - 3.05	3.05
Sand, fine to medium grained, brown fine grained	3.05 - 6.10	3.05
Sand, coarse, to very coarse gravelly, subangular to sub rounded, yellowish grey with lenticles of bluish grey clay and inclusions of lateritic grains to shells	6.10 - 9.14	3.04
Sand, coarse, yellowish to grey clayey, with inclusions of shells, laterite	9.14 - 12.19	3.05
Clay, bluish, grey, sticky, plastic, intercalated with coarse grained sand and inclusions of shells	12.19 - 15.24	3.05
Clay, sandy, bluish grey	15.24 - 18.29	3.05
Sand, coarse to very coarse, subrounded, yellowish grey, intercalated with bluish grey, sticky clay	18.29 - 21.34	3.05
Clay, bluish grey, sticky, plastic with minor sand streaks	21.34 - 24.38	3.04
Clay, bluish grey to dark grey, sticky	24.38 - 27.43	3.05
Clay, bluish grey to dark grey, sticky with a little sand and inclusion of laterite and calcareous material	27.43 - 30.48	3.05
Sand, clayey, coarse to very coarse bluish grey to yellowish grey with inclusion of greenish material	30.48 - 33.53	3.05
Sand coarse to very coarse, sub rounded yellowish grey with minor shell inclusions	33.53 - 36.58	3.05

(contd . . . . . .)

Lithology	Depth range (m)	Thickness (m)
Sand, very coarse to gravelly with minor intercalation of bluish grey to yellowish grey clay	36.58 - 39.62	3.05
Sand, very coarse to gravelly with minor intercalation of bluish grey to yellowish grey clay with minor lignite lenticles and yellow ochre	39.62 - 42.67	3.05
Sand, very coarse to gravelly, grey, sub rounded	42.67 - 45.72	3.05
Sand, coarse to very coarse, sub rounded whitish grey, clayey	45.72 - 48.77	3.05
Sand, medium to coarse sub rounded with occasional gravel, intercalated with yellowish grey clay	48.77 - 51.82	3.05
Sand, coarse to very coarse, sub angular to sub rounded with inclusion of marcasite	51.82 - 54.86	3.04
Sand, coarse to very coarse, sub angular to sub rounded with inclusion of marcasite with little whitish to greyish clay, plastic, sticky and inclusion of laterite	54.86 - 57.91	3.05
Sand, coarse to very coarse, sub rounded yellowish grey with minor intercalation of clay of dark grey to bluish grey and marcasite	57.91 - 60.96	3.05
Gravel, sub rounded to rounded greyish with inclusion of marcasite	64.04 - 67.06	3.05
Gravel, sub rounded to rounded greyish with inclusion of marcasite intercalated with whitish kaolinised clay	67.06 - 70.10	3.04

(contd . . . . .)

Lithology	Depth range (m)	Thickness (m)
Clay, whitish to grey, plastic, sticky intercalated with medium grained sand and mica	70.10 - 73.15	3.05
Weathered biolite gneiss with lot of quartz pebbles and a little kaolinite clay	73.15 - 76.20	3.05
Weathered biolite gneiss with lot of quartz pebbles and a little kaolinitic clay	76.20 - 79.25	3.05

Appendix II. Lithology of Tallikulam site

Lithology	Depth range (m)	Thickness (m)
Sand, fine to medium, sub rounded greyish white with ferruginious minerals	0 - 6.10	6.10
Sand, medium to coarse, sub angular to sub rounded, yellowish grey with abundance of shells	6.10 - 13.71	7.61
Laterite, brown to dark brown, gravelly admixed with yellowish grey, coarse grained sand and a little clay and shells	13.71 - 17.07	3.36
Sand, coarse grained, sub angular to sub rounded, yellowish grey with laterite gravels and minor speck of whitish clay	17.07 - 21.34	4.27
Sand, very coarse grained to gravelly sub angular to sub rounded, whitish to yellowish with inclusions of lateritic gravel and shells	21.34 - 25.60	4.26
Sand, very coarse grained to gravelly sub angular, yellowish grey with abundance of dark brown carbonaceous clay, lignite, calcareous matter and shells	25.60 - 28.04	2.44
Sand, coarse to very coarse sub angular to sub rounded yellowish grey to whitish	28.04 - 35.97	7.93
Sand, very coarse grained, sub angular, grey, intercalated with carbonaceous clay and lignite	35.97 - 39.62	3.05
Carbonaceous clay and lignite admixed with very coarse to gravelly sand	39.62 - 51.82	12.20

(contd . . . . .)

Lithology	Depth range (m)	Thickness (m)
Sand, coarse to very coarse grained sub angular to sub rounded, yellowish grey to whitish with inclusions of marcasite	51.82 - 59.74	7.92
Sand, very coarse to gravelly, sub angular to sub rounded, yellowish grey to whitish intercalated with whitish to greyish clay with inclusions of marcasite and ferromagnesian minerals	59.74 - 64.0	4.26
Clay, lithomargic, whitish to pale grey plastic, admixed with coarse to very coarse sand pieces and ferromagnesian minerals	64.0 - 73.15	9.15
Weathered biolite gneiss	73.15 - 79.25	6.1

Appendix III. Lithology of Kazhimbram site

Lithology	Depth range (m)	Thickness (m)
Sand, fine to medium grained, sub angular to sub rounded, brown admixed with ferromagnesian minerals, lateritic gravels	0 - 12.19	12.19
Sand, medium to coarse, sub angular to sub rounded, yellowish brown to grey admixed with laterite and shells	12.19 - 15.24	3.05
Sand, coarse to very coarse grained at place gravelly, sub angular to sub rounded with minor streaks of fine sand and with very minor traces of greyish clay and inclusions of shells, ferromagnesium minerals	15.24 - 27.43	12.19
Clay, bluish grey, semi plastic, sticky with minor streaks of coarse to very coarse sand	27.43 - 30.48	3.05
Sand, clayey, coarse to very coarse sub angular, yellowish grey to whitish, admixed with clay of bluish grey, sticky, plastic with inclusions of carbonaceous matter	30.48 - 33.53	3.05
Clay, bluish grey, hard, sticky plastic with inclusions of carbonaceous particles	33.53 - 45.72	12.19
Sand, very coarse to gravelly sub angular, yellowish grey, intercalated with bluish grey to yellowish grey clay	45.72 - 48.77	3.05

(contd . . . . .)

Lithology	Depth range (m)	Thickness (m)
Gravel, sub angular, yellowish grey to grey with very minor streaks of bluish grey clay which becomes kaolinitic towards the bottom	48.77 - 64.01	15.24
Gravel, with abundance for fieldspar ferromagnesians intercalated with more of kaolinite clay	64.01 - 70.10	6.09
Clay, dirty white to buff colour, kaolonite, sticky, with abundance of quartz, weathered fieldspar and ferromagnesian minerals	70.10 - 73.15	3.05

Appendix IV. Values of coefficient of permeability

Soil type	Coefficient of permeability (m/day)		
Limestone	0.0000004	-	0.00008
Sandstone	0.00012	-	1.2
Clay	0.00004	-	0.04
Silt	0.04	-	0.4
Very fine sand	0.4	-	4.0
Fine sand	4.0	-	40.0
Medium Sand	40.0	-	180.0
Coarse sand	180.0	-	260.0
Very coarse sand	260.0	-	320.0
Very fine gravel	320.0	-	450.0
Fine gravel	450.0	-	640.0
Medium gravel	640.0	-	900.0
Coarse gravel	900.0	-	1200.0
Very coarse gravel	1200.0	-	1600.0

Appendix V. Values of porosity

Material	Porosity
Soils	50 - 60
Clay	45 - 55
Silt	40 - 50
Medium to coarse mixed sand	35 - 40
Uniform sand	30 - 40
Fine to medium mixed sand	30 - 35
Gravel	30 - 40
Gravel and sand	20 - 35
Sandstone	10 - 20
Shale	1 - 10
Limestone	1 - 10

Appendix VI. Computer programme

```
      DIMENSION Y (40), Q2F (40), C (40), QF1 (40), QF (40), PR (40)
      READ (1, 40) ALFA, AK, X, QI, N
40    FORMAT (4F8.3, I2)
      DO 2 I = 1, N
  C   ALFA    IS   THE EXCESS DENSITY RATIO
  C   AK      IS   THE COF. OF PERMEABILITY OF AQUIFER
  C   AK      IS   THE X CORDINATE OF INTERFACE
  C   QI      IS   THE INITIAL DISCHARGE
  C   N       IS   THE NUMBER OF OBSERVATIONS
      READ (1, 30) Y (I)
30    FORMAT (F8.3)
2     CONTINUE
      A1 = .52/(ALFA*AK)
      B1 = 2*X/(1 + ALFA)
      DO 3 I = 1, N
      C (I) = -1*ALFA*AK*Y (I)*Y(I)
      QF1(I)=SQRT(B1*B1-4*A1*C(I))
      QF(I)=-1*(-B1+QF1(I))/(2*A1)
      Q2F(I)=-1*(-B1-QF1(I))/(2*A1)
      PR(I)=(ABS(QI)-ABS(QF(I)))
      WRITE (2,20)Y(I),Q2F(I),QF(I),PR(I)
20    FORMAT (4E15.8)
3     CONTINUE
      STOP
      END
```

SEAWATER INTRUSION STUDIES FOR COASTAL AQUIFERS

By

SALEY ABRAHAM

ABSTRACT OF A THESIS

Submitted in partial fulfilment of the
requirement for the degree

Master of Science in Agricultural Engineering

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ABSTRACT

Studies were conducted in three villages along the coastal areas of Trichur district, namely, Nattika, Tallikulam and Edamuttam, to know the extent of sea water intrusion through aquifers. Observations were made in existing wells along an alignment normal to the coast line. Aquifer parameters and fresh water flow through the aquifer were computed making use of borehole data available for the region. The positions of the interfaces were determined using established formulae. The possible shifting of the interfaces due to reduction in fresh water discharge consequent to future increased rate of pumping was predicted. In each village, three wells were taken for the study purpose. In all the cases, the maximum rates of pumping for various depths of wells, which will not cause sea water intrusion problems, have been determined. Chemical analysis showed that, at present there was no salt water intrusion in the wells under study.

The results of the present study lead to a better understanding of the sea water intrusion problem, the determination of the position of the interfaces for various pumping rates might be effectively used in fixing the location of wells, pumping rates and depth of wells. The study would be made use of designing a ground water system in coastal areas for a better utilisation of ground water resources.