NORSK INSTITUTT FOR VANNFORSKNING
Blindern

# Flow Conditions in Glåma Estuary
## (Phase I)

Siv.ing. Yasar Fahri Öztürk

Blindern, april 1969

# CONCENTRATION

# I INTRODUCTION

Glåma estuary is one of the very important locations in Norway. It provides harbors, transportation routes, best places for several industrial plants, recreational areas for hunting, swimming, boating etc. During the last years the rapid growth of population and industrial expension in the Glåma river area have resulted in production of considerable amount domestic and industrial wastes to be disposed into the estuary, and this situation is expected to increase from the present level.

As mentioned above, Glåma estuary have many advantages and therefore increasing human activities in this area is treating the estuary which makes necessary a through pollution control planning for the matter. This is important to predict the degree of treatment and quantities of domestic and industrial wastes which can be tolerated by the estuary system.

Investigations show that wastes disposed into the estuary destroy the quality of the water and biological life in the estuary. Although there are several other aspects such as erosion, sedimentation, siltation, saltation, chemical and biological changes which have to be considered to protect and keep the Glåma estuary in good conditions, the objective of the following presentation is restricted to the matters to understand the fresh water and salt water movements and their influence on mixing and distribution of salt water which provide the basis for the solution of industrial and human use of the estuary waters and pollution problems.

The evaluation of above mentioned matters for Glåma estuary from the existing data given in literature seems difficult or impossible, as the range of conditions found in various estuaries are not the same. Considering that estuary conditions changing from place to place, to find an answer for the solution of the problem from model investigations in many cases may be risky also. Therefore related investigation requires a through field data, as the state of knowledge for the matter is still inperfect and offered principals from model investigations are not generalized yet. On the other hand obtained field data for this investigation is limited which is also not enough to judge on flow conditions in the estuary in question.

As a first step, in the following the salt intrusion length, position of fresh-salt water interface and amount of seaward flow which are essential factors to determine the fresh water and salt water movements, mixing and distribution of salt water in the estuary are investigated.

A theoretical relationship adopted for the calculation of salt intrusion length has given good result and is in good agreement with the field observation. It is observed that the theoretical position of fresh-salt water interface has no practical importance in our case, instead zero velocity line which is below the fresh-salt water interface has to be considered.

Possibilities of practical evaluation of the position of zero velocity line to be considered in the evaluation of seaward flow, will be very beneficial to determine mixing and distribution of salt water. This is very important specially in calculating the detention time of nonconservative contaminants discharged into estuary.

## II THE SYSTEM OF GLÅMA ESTUARY

Glåma river (Fig. 1) which is the largest river in Norway has a catchment area of 41 425 $km^2$ and at its lower part the average flow of 700 $m^3/sec$. The tidal range and flow ratio (based on average flow) are 13 cm and 17:1 respectively.

Changing flow conditions and various salinity distribution in the estuary during the different times of the year are mostly the result of the considerable degree of fluctuations in the river flow (400 - 1200 $m^3/sec.$, Fig. 2). It is observed that Glåma estuary is a halocline salt wedge estuary, salinity variation between the upper and lower limits of halocline is not through. Due to the very low tidal range of 13 cm, the horizontal position and vertical dimensions of the wedge are mostly controlled by the river flow.

Field observations in Glåma estuary show that seaward flowing fresh water entrains seawater from the below and form a halocline in which salinity increases with depth and seaward. As can be seen from the Figs. 3 and 4 the salinity in the vicinity of the upper limit of halocline is neglibible, and the salinity in the lower zone is the same of the adjacent seawater. The vertical velocity distribution of flow in the estuary shows that mixing between fresh water and salt water occur within the halocline and seaward movement is over the the zero velocity line. The mixing under such conditions cause the vertical exchange of fresh and salt water elements and the variation of their density. As a result fluid elements become unstable and cannot return to their orginal positions. The halocline formed this way introduce a salinity gradient between the upper and lower zones. It seems that the downward transfer of fresh water is causing the creation of halocline. The movement of water below the zero velocity line is in the upstream direction and slight salinity gradient within this part of halocline is due to the mixing forces which should be effective untill the lower limiting line.

In the following, obtained limited parameters for the evaluation of the matters in question are related to the principals developed for the arrested saline wedges. To use such data for a halocline salt wedge, it is assumed that maximum intrusion length of halocline salt wedge is equal to the intrusion length of stationary salt wedge, and the salt content of a vertical column of water is the same whether the salt is confined to a wedge or mixed throughout the column.

## III SALT WEDGE ESTUARY

In many estuaries during the seasons of reduced river discharges and in the absence of tide, the fresh and salt water layers remain separate. Due to the density difference between these water layers which causes the gravitational currents, the interface may be turbulant and mixing may exist, but for the solution of some related problems it is always assumed that the salt wedge is in the still form and the layers remain constant over the entire intrusion length.

As a matter of fact when the average velocity of flow in the river exceeds the limiting velocity, internal waves form at the interface and cause the elements of seawater to be entrained in the freshwater layer. Under such conditions flow just under and over the sea-fresh water interface is in the same direction of that fresh water, but, in the vicinity of the bottom is otherwise.

The rate of seawater flowing in the upstream direction decreases and seawater moving upstream near the bottom is balanced by the same amount of its seaward flow. The decrease in flow rate in the wedge in the upstream direction is evidence for the vertical transport of salt water through the interface. As a result while freshwater flows seaward its salt content, volume and velocity of flow increases and reach maximum near the estuary entrance.

## IV STATIONARY SALT WEDGE

The motion of salt wedge from the tideless sea into river channel is treated on the basis of density currents. Although the geometry of estuaries may vary from place to place, the one which is adopted for the analytical evaluation is the channel of constant shape, and the influence of the local variations in depth, width, velocity and salinity are not considered. The following treatment is restricted to the case of rectangular cross section of width B and depth H, in which the salt wedge is assumed to be, in still form, and fresh and salt water distinctly layered over the entire intrusion length. The properties of such an estuary system can be described by its own variables, which are

Lo, H, B. hsi, hs, Vr, V$\Delta$, $\nu$

where

Lo = salt intrusion length
H = depth of river at river mouth
hs = hight of salt wedge at any point along the wedge
hsi = hight of salt wedge at river mouth
Vr = average velocity of river opposing advancing wedge

$V$ = densimetric velocity $(\frac{\Delta\rho}{\rho m} g H)^{\frac{1}{2}}$

$\rho$ = density of fresh water

$\rho+\Delta\rho$ = density of sea water

$\rho m$ = average density of two liquids

$g$ = acceleration of gravity

$\nu$ = kinematic viscosity of water

The dimensionless analysis have shown that all the variables given above are functions of two parameters $F\Delta$ and $R\Delta$, densimetric Froude number and densimetric Reynolds number respectively

$$F\Delta = \frac{Vr}{(\frac{\Delta\rho}{\rho m} g H)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$R\Delta = \frac{V\Delta H}{\nu} \quad \ldots\ldots\ldots\ldots \quad (2)$$

Existing information about the subject of this investigation is limited, in the following, the present and extensive study based on model studies for the evaluation of salt intrusion length and position of fresh-salt water interface proposed by Keulegan (1) is reviewed.

## 1. Salt intrusion length

$$\frac{Lo}{H} = f\,(\frac{Vr}{V\Delta}, \frac{V\Delta H}{\nu}, \frac{H}{B}) \quad \ldots\ldots\ldots\ldots \quad (3)$$

Based on the above dimensionless relationship and experimental channels of depth-with ratios, $H/B \simeq 1 - 2$, the following relationship was given

$$\frac{Lo}{H} = A\,(\frac{2Vr}{V\Delta})^{-n} \quad \ldots\ldots\ldots\ldots \quad (4)$$

and the salt intrusion length was expressed in the following form

$$\frac{Lo}{H} = Ao(\frac{V\Delta H}{\nu})^{m}\,(\frac{2Vr}{V\Delta})^{-n} \quad \ldots\ldots\ldots\ldots \quad (5)$$

The evaluation of Eq. 5 depends on the accurate determination of Ao, m and n. Considering the river Reynolds number exceeding the critical value at the upstream of salt wedge, a value of -5/2 was given for n, which is the slope of the lines produced as a result of the plot of Lo/H against 2 F$\Delta$ (fig. 5). With reference to Fig. 6, which gives a relationship between the variable A in Eq. 4 and densimetric Reynolds number, Ao varies with H/B and densimetric Reynolds number. By assuming the interface and bottom resistances for both laboratory and actual conditions being the same, for the calculation of the salt intrusion length under different estuary conditions the following values were given for Ao, m and n.

| Ao | m | n | H/B | R$\Delta$ |
|---|---|---|---|---|
| 0.23 | 1/2 | 5/2 | - | order of $10^4$ - $10^5$ |
| 0.18 | " | " | 1 | - " - |
| 0.12 | " | " | 2 | - " - |
| 6 | 1/4 | " | - | order of $10^7$ or greater |

Substituting 6, 1/4, and -5/2 for Ao, m and n respectively in Eq. 5, the salt intrusion length in the Mississippi river were calculated, where calculated and observed values were shown to be in good agreement. On the other hand based on the experimentally evaluated and theoretically generilized stresses of model estuaries, the following equations were given for the evaluation of A to be used in Eq. 4.

For estuaries of large width in comparision with depth

$$A = \frac{0.88}{280\left(\frac{V_\Delta H}{\nu}\right)^{-1} + 0.148\left(\frac{V_\Delta H}{\nu}\right)^{-1/4}} \quad \ldots\ldots\ldots\ldots \quad (6)$$

For R$\Delta$ of the order of $10^4$

$$A = 0.23 \left(\frac{V_\Delta H}{\nu}\right)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

For $R_\Delta$ of the order of $10^7$ or greater

$$A = 6.0 \left(\frac{V_\Delta H}{\nu}\right)^{1/4} \qquad (8)$$

## 2. Position of fresh-salt water interface

Investigations have shown that the shape of the arrested salt wedges are practically affine to each other and this affiness was expressed as

$$\frac{hs}{hsi} = f\left(\frac{L}{Lo}\right). \qquad (9)$$

where

L = distance in terms of wedge length Lo

On the other hand the ratio of the salt wedge depth at the river mouth to the total water depth as a function of densimetric Froude number for stationary salt wedge was given by

$$\frac{hsi}{H} = 1 - \frac{1}{2^{2/3}} \left(\frac{2Vr}{V\Delta}\right)^{2/3} \qquad (10)$$

The difference between the results of the above equation and observed values increases as 2 $Vr/V\Delta$ approaches zero. There is satisfactory agreement between theoretical and observed values when 2 $Vr/V\Delta$ is close to unity. For known 2 $Vr/V\Delta$ and L the use of laboratory data given by Figs. 7 and 8 makes possible to determine the position of fresh-salt water interface in a stationary salt wedge estuary. According to the relationships given in Fig. 8 the hight of salt wedge at the river mouth is variable and its variation is controlled by the velocity of river flow opposing the wedge.

It seems that the hight of salt wedge hsi which is assumed to exist at the river mouth for low river discharges, is pushed seaward with the increasing river discharges. hsi may be constant but not stationary and its position depends on the river discharge.

## 3. Practical use of above given data

It is tried to evaluate the salt intrusion length in Glåma estuary through the above given imformation.

The width of Glåma estuary is considerably large in comparison to its depth. Therefore to calculate the salt intrusion length, $\Lambda$ to be used in Eq. 4 is evaluated through Eq. 8. As shown in the following there is a very good agreement between calculated and observed salt intrusion lengths.

$$Vr = 0.36 \text{ m/sec.}$$

$$V\Lambda = 1.30 \text{ "}$$

$$\frac{2Vr}{V\Lambda} = 0.55$$

$$\frac{V\Lambda\ H}{\nu} = 9.75 \cdot 10^6$$

| | calculated | observed |
|---|---|---|
| Salt intrusion length in Glåma estuary | 13,716 m | 13,500 m |

It is obvious that the salt intrusion length in such a halocline salt wedge estuary can be evaluated from the principals of stationary salt wedge estuary.

In the above given equations the value of n is constant for all cases, and the validity of these relationships depend on the accurate determination of $\Lambda o$ and m. From the scatter and limited range of data given in Fig. 6, it is obvious that the results from such model investigations cannot be extrapolated to many actual estuaries satisfactorily. On the other hand the accurate deterination of $\Lambda o$ and m, which are governing parameters of salt intrusion length equation, obviously is not easy by the above mentioned process.

## 4. Evaluation of $\Lambda o$ and m

Instead of considering the relationship between $\Lambda$ and $R\Lambda$, the relationship between $2F\Lambda$ and $R_\Lambda$ is established from Fig. 5, Lo/H as third variable. As can be seen from Fig. 9 the double logaritmic plot of 2FΔ and RΔ should yield values of constant k and gradient m´ which can be expressed by

$$\frac{2Vr}{V\Delta} = k\left(\frac{V\Delta\ H}{\nu}\right)^{m'} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

On the other hand an equation relating the three variables can be developed by plotting Lo/H, the value of k, the intercept on 2FΔ - axis for RΔ = 1 for each line of constant Lo/H. From Fig. 9 these intercepts designated k are plotted against Lo/H in Fig. 10. The equation resulting from Fig. 10 is

$$\frac{Lo}{H} = Ao\ k^{-n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

The Eqs. 11 and 12 are combined to yield the following salt intrusion length equation

$$\frac{Lo}{H} = Ao\left(\frac{V\Delta\ H}{\nu}\right)^{m'n}\left(\frac{2Vr}{V\Delta}\right)^{-n} \quad \ldots\ldots\ldots\ldots \quad (13)$$

where m´n = m, and Eq. 13 is the same as Eq. 5.

Although available data in the above process is limited, Eqs. 12 and 13 show that n is constant and m depends on m´, which is expected to vary with the varying conditions of estuaries.

It is observed that to calculate the salt intrusion lengths in Glåma and Mississippi estuaries the salt intrusion length equation of the following form would be satisfactory

$$\frac{Lo}{H} = 6\left(\frac{V\Delta\ H}{\nu}\right)^{1/4}\left(\frac{2Vr}{V\Delta}\right)^{-5/2} \quad \ldots\ldots\ldots\ldots \quad (14)$$

Under such conditions taking Ao = 6 on $\frac{Lo}{H}$ -axis for 1/k = 1 in Fig. 10 and draw a line having a gradient n = 5/2 from the intercept, makes possible to evaluate the salt intrusion lengths corresponding to different river discharges in the mentioned estuaries. Such arrangement is possible in the case Ao and m are known. As mentioned previously through the available data the accurate determination of Ao and m is not easy and from the above analytical investigation it is clear that the geometry of the estuary greatly affects Ao and m which are characteristic estuary parameters.

## V QUANTITY OF SEAWARD FLOW

The quantity of seaward flowing brackish water can be determined on the basis of flow measurement by dilution method. Using the river water as a tracer, the comparision of river water concentration at the tip of the salt wedge and in the seaward flowing brackish water will be sufficient for the matter.

The mass flow of river water at the tip of the wedge should be equal to the mass of river water after it arrives at the point of interest.

Thus,

$$qr\ Cr + qs\ Cs = (qr + qs)\ Cb \qquad (15)$$

where

$qr$ = rate of river flow
$qs$ = rate of seawater flow
$Cr$ = concentration of river water at tip of wedge
$Cs$ = concentration of river water in seawater
$Cb$ = concentration of river water in seaward flowing brackish water
$Cr = 1$
$Cs = 0$

$$qr = (qr + qs)\ Cb \qquad (16)$$

where $(qr + qs)$ is the total volume of seaward flow at the point of interest, and showing, $qr + qs = Q$, the rate of seaward flow can be expressed by

$$Q = \frac{qr}{Cb} \qquad (17)$$

The determination of seaward flow by Eq. 17 is completely independent of flow velocity and estuary dimensions. As is obvious the relative error in determining seaward flow this way will be equal to the relative error in the determination of the concentration of river water at the point of interest.

## 1. Determination of Cb

If the salinity distribution is uniform over the cross-section of seaward flowing brackish water layer, the river water concentration can be determined by

$$Cb = \frac{S - Sb}{S} \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

where

$S$ = salinity of undiluted seawater
$Sb$ = salinity of the sample

Where considerable salinity gradient exists such as in halocline salt wedge estuaries, the river water concentration in seaward flowing brackish water can be evaluated better by the following relationship (2)

$$Cb = \frac{SL - \int_0^L s\,dz}{SL} \quad \ldots\ldots\ldots\ldots\ldots \quad (19)$$

where

$L$ = lower limit of halocline
$z$ = depth pozitive downward
$s$ = salinity at depth $z$

The use of Eq. 19 is achieved conveniently by plotting the salinity data as a function of depth, from where the numerator can be obtained by planimetric integration of the area between depth-salinity relation and salinity of undiluted seawater. The nominator is the area expressed as a production of the undiluted seawater salinity and depth of the lower limit of halocline.

## 2. Evaluation of seaward flow in Glåma estuary

As mentioned previously, Glåma estuary is a halocline salt wedge estuary in which salinity distribution is not uniform over the cross-section area of interest. Under such conditions Cb to be used in Eq. 17, to calculate the quality of seaward flow in Glåma estuary, is evaluated by Eq. 19.

Calculated seaward flow is given in Fig. 11, which shows flow increases seaward considerably.

## VI RESULTS OF INVESTIGATION AND CONCLUSION

Considering the present and future importance of Glåma estuary, the knowledge of flow conditions in the Glåma estuary will provide the basis for the solution of many practical problems.

This investigation is the first phase and include the aspects necessary to develop a matematical model which will accurately describe the mixing and distribution of salt water in the Glåma estuary.

Theoretically evaluated salt intrusion length in the Glåma estuary is in very good agreement with the observed salt intrusion length, and a relationship offered will make possible to evaluate the salt intrusion lengths corresponding to different river discharges in Glåma estuary.

As seaward flow is over zero velocity line, a practical evaluation of the position of zero velocity line instead of interface will have great significance for the investigation of mixing and distribution of salt water in the estuary.

For the second phase investigation a through field data is necessary to evaluate the mixing and distribution of salt water necessary for the prediction of problems in question.

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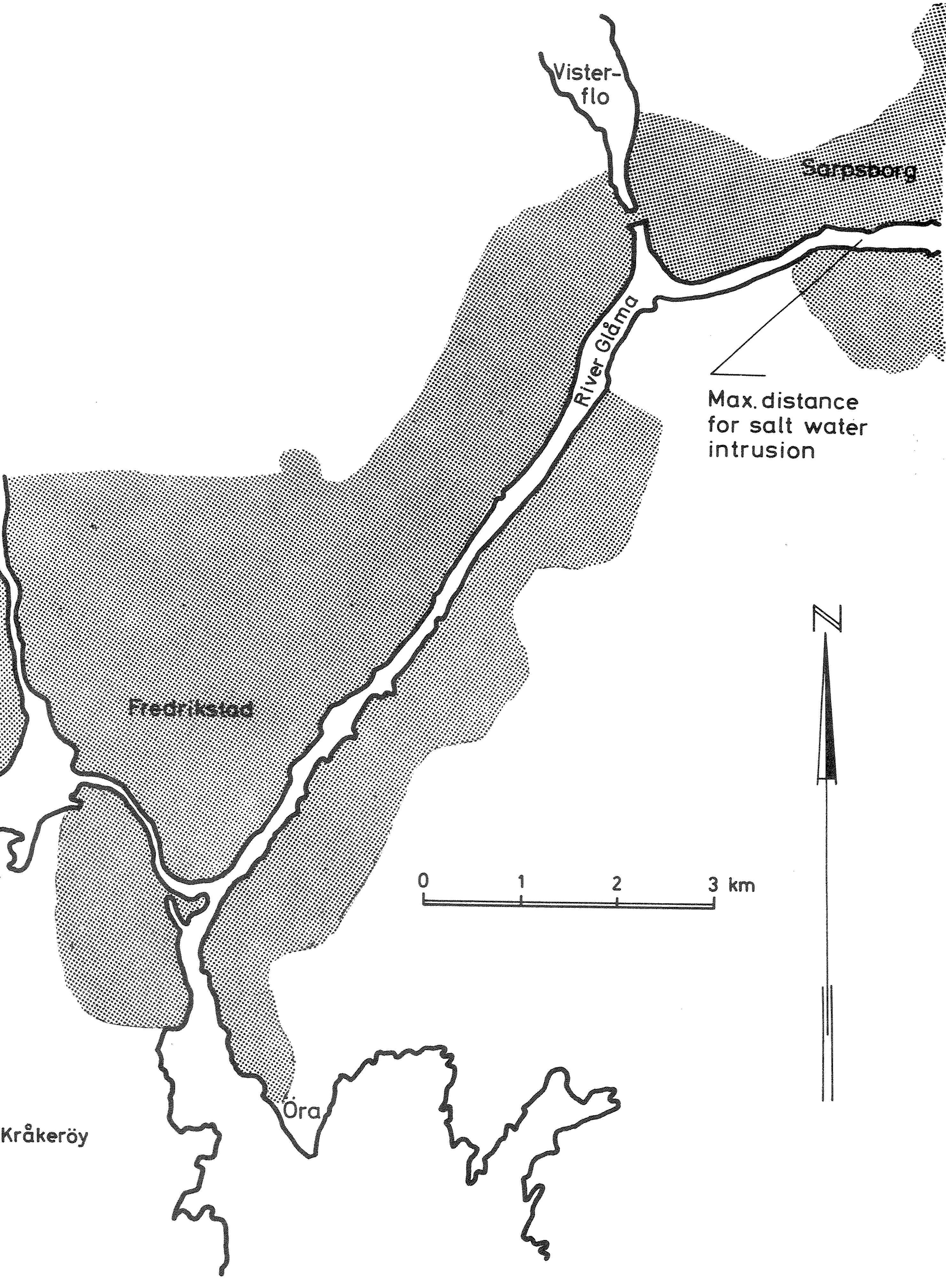
## REFERENCES

1. Keulegan, G.H., "The Mechanism of an Arrested Saline Wedge", Estuary and Costline Hydrodynamics, edited by A.T. Ippen, Mc. Graw-Hill, 1966

2. Tully, J.P., "On Structure, Entrainment and Transport in Estuarine Embayments, Journal of Marine Research, Vol. 17, 1958.


Vister-
flo
Sarpsborg
River Glåma
Max. distance
for salt water
intrusion
N
Fredrikstad
0
1
2
3 km
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Kråkeröy

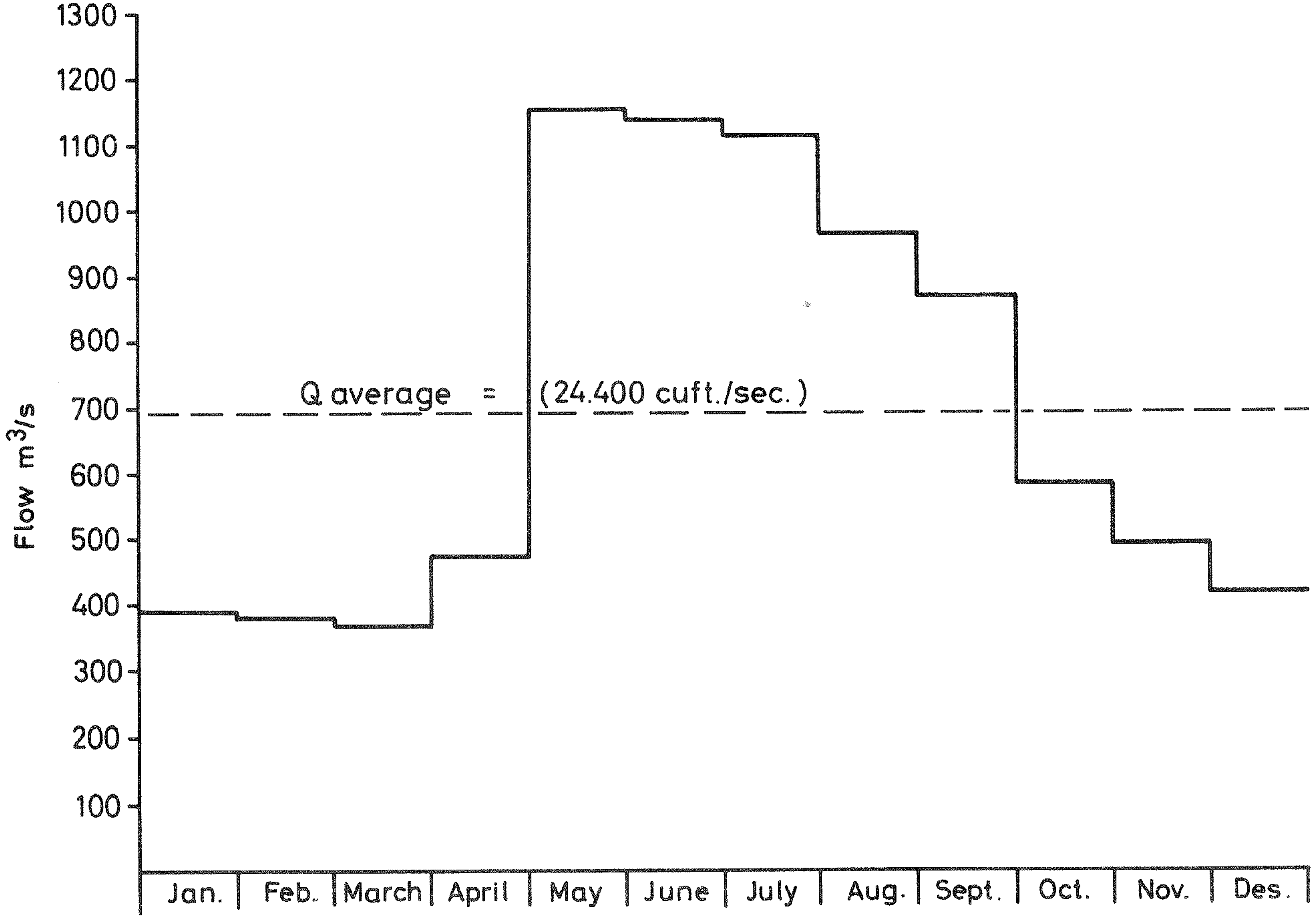

Fig. 2. Average monthy flow in the lower part of River Glåma during the period 1950-1959

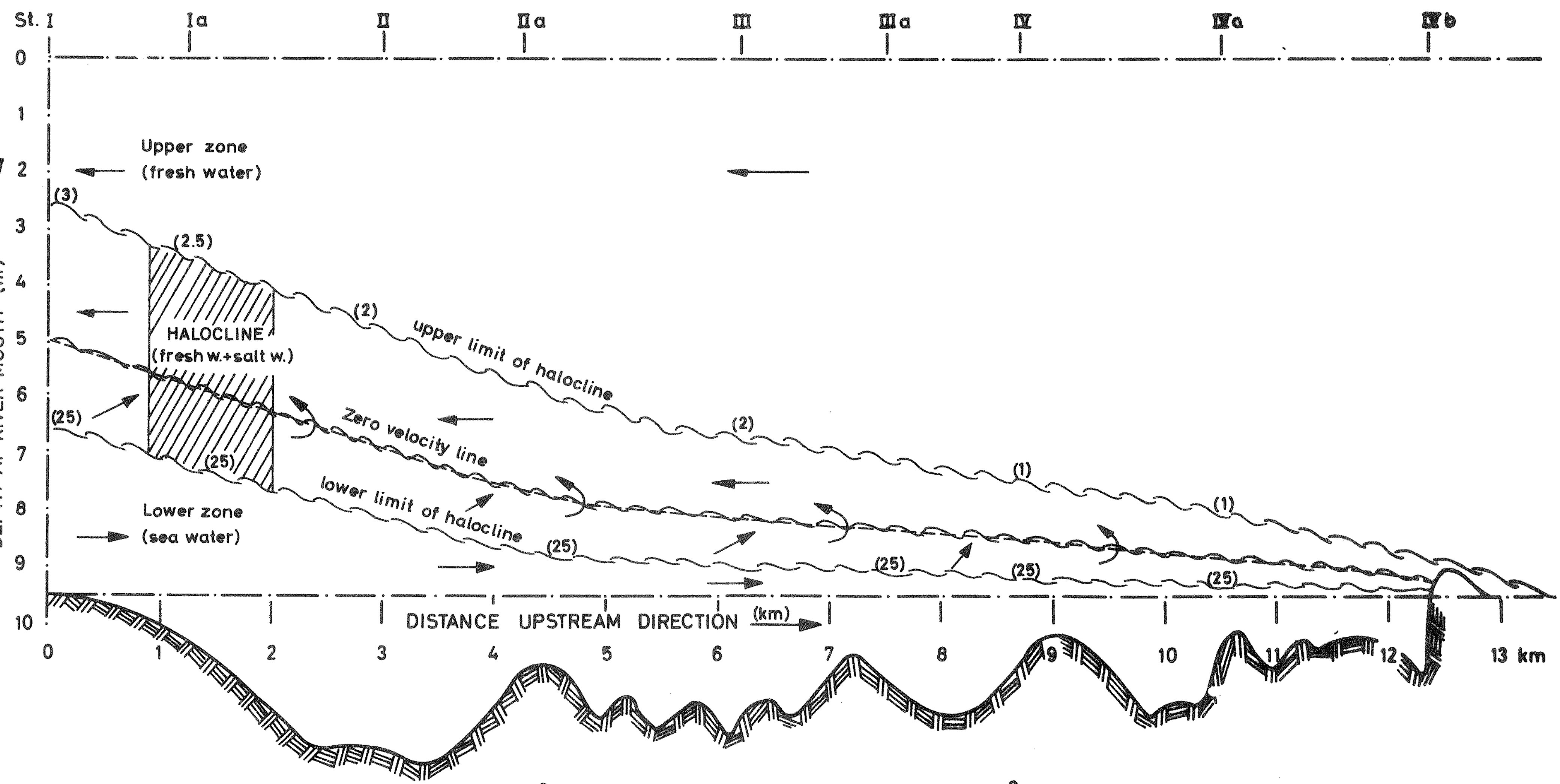

Fig. 3. HALOCLINE SALT WEDGE (Q = 448 $m^3$/sec.)
(3), (25), ---- show salinity

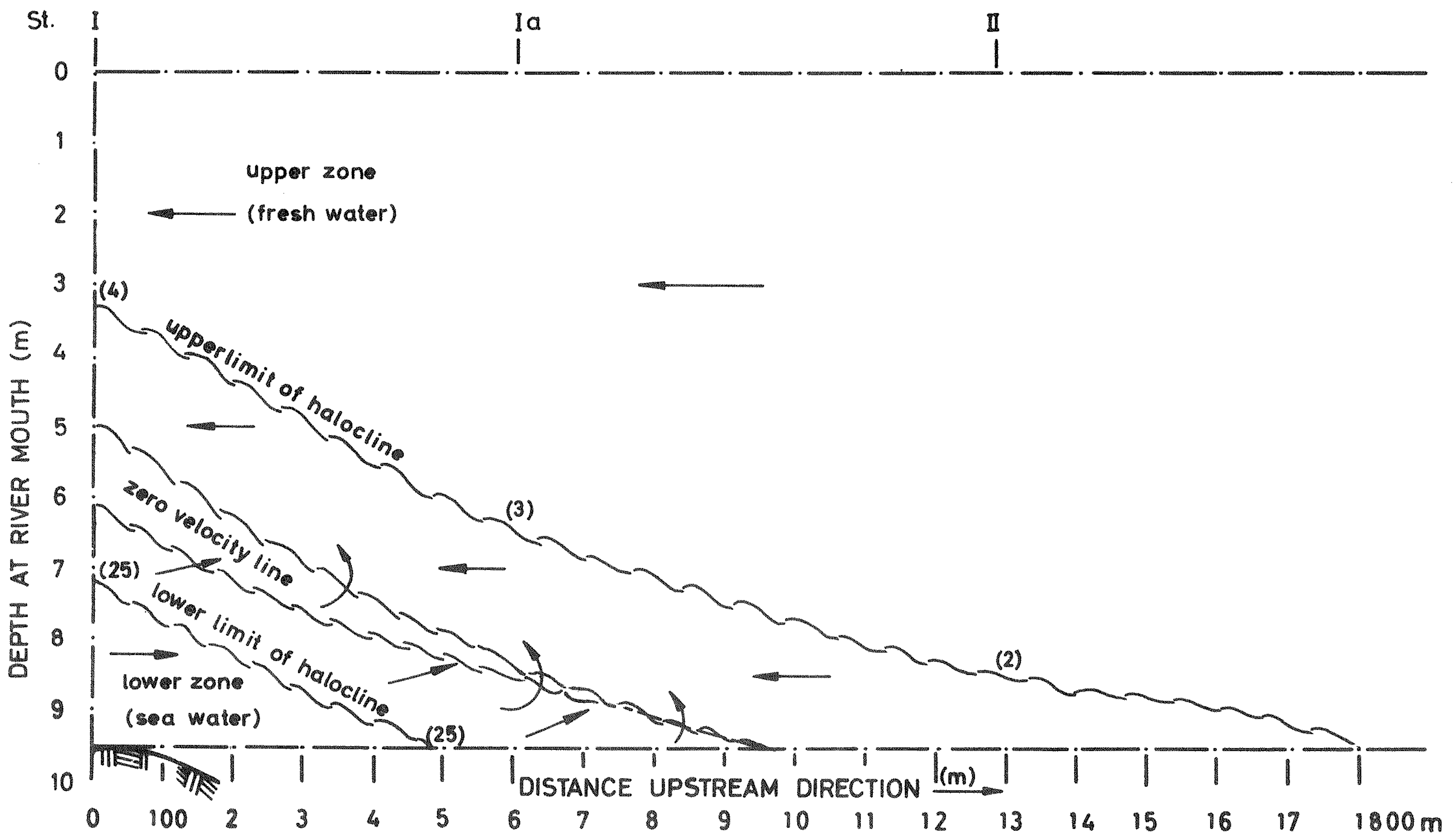

Fig. 4. HALOCLINE SALT WEDGE (Q = 1246 $m^3$/sec.)
(3),(25),---- show salinity

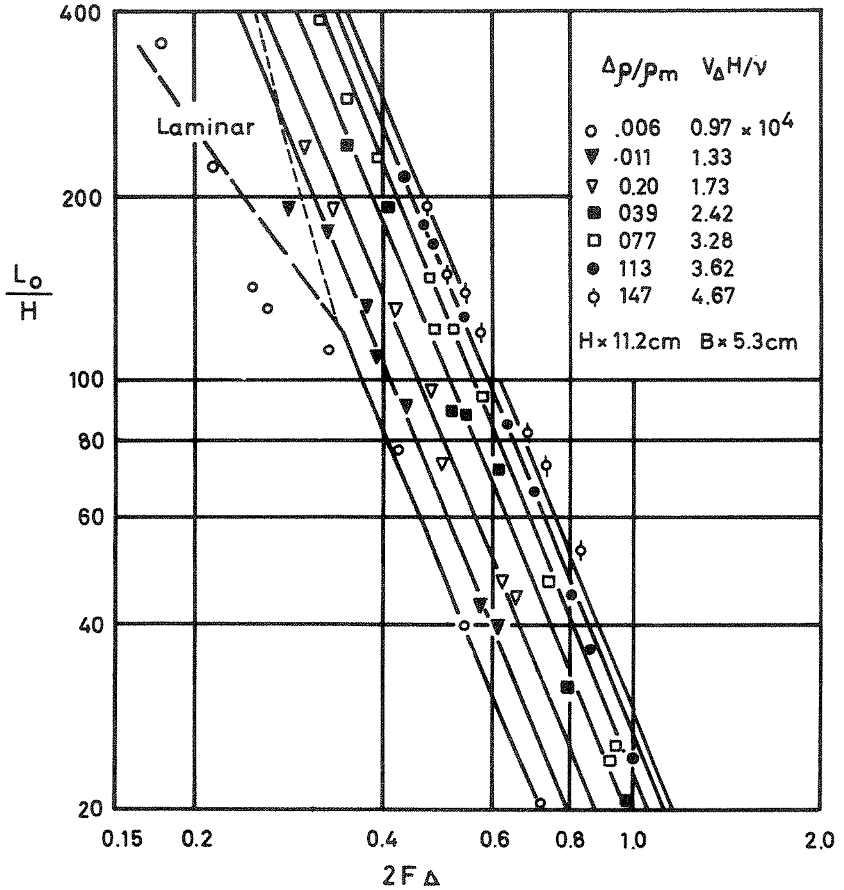

Fig. 5. Length of arrested saline wedge (after keulegan).

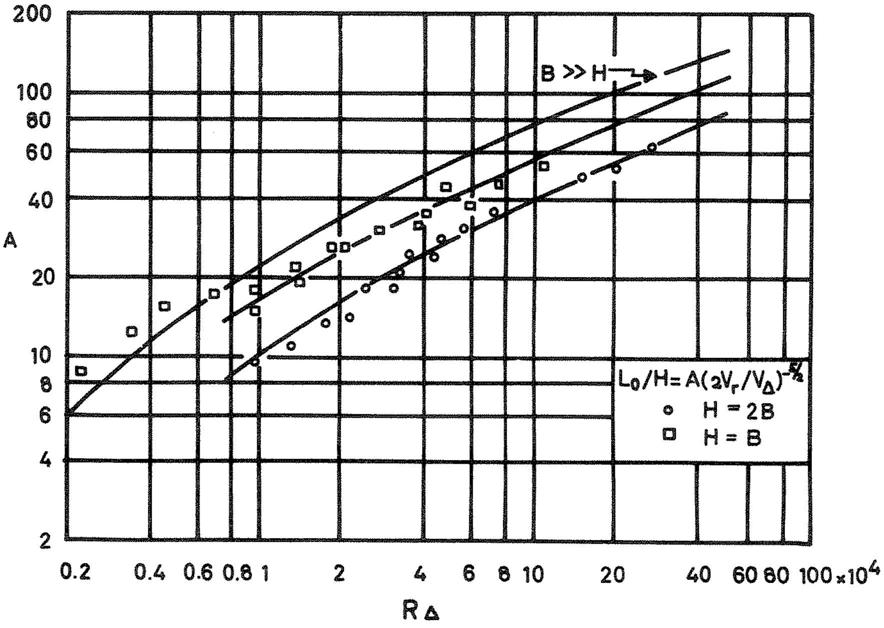

Fig. 6. Effect of channel width on arrested saline wedges (after keulegan)

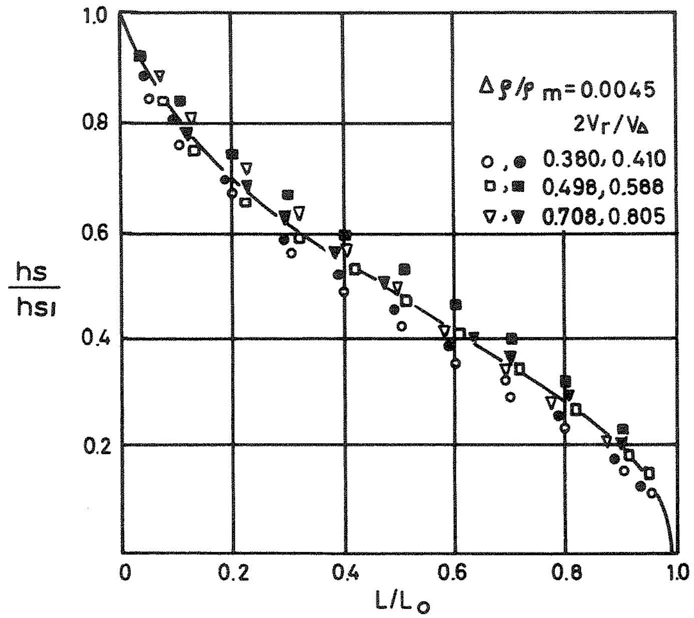

Fig. 7. Affine form of arrested saline wedges
(after keulegan)

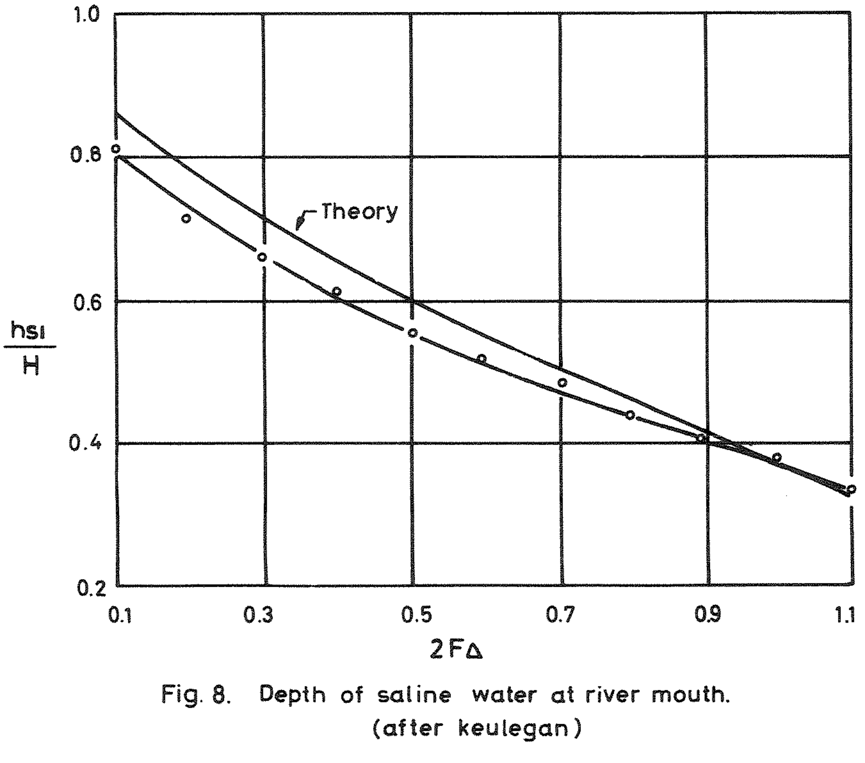

Fig. 8. Depth of saline water at river mouth.
(after keulegan)

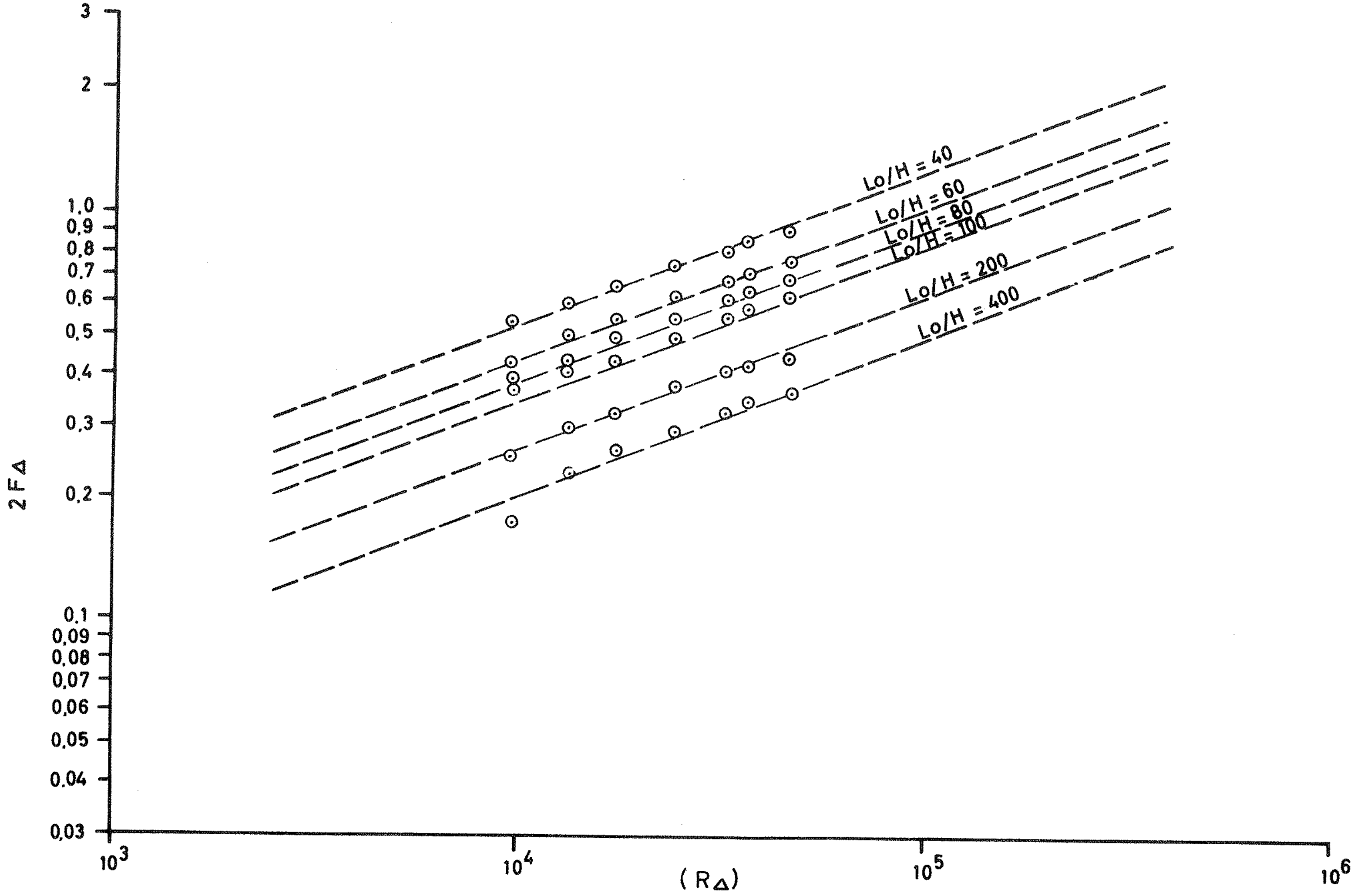

Fig.9 Densimetric Froud and Reynold numbers relationship

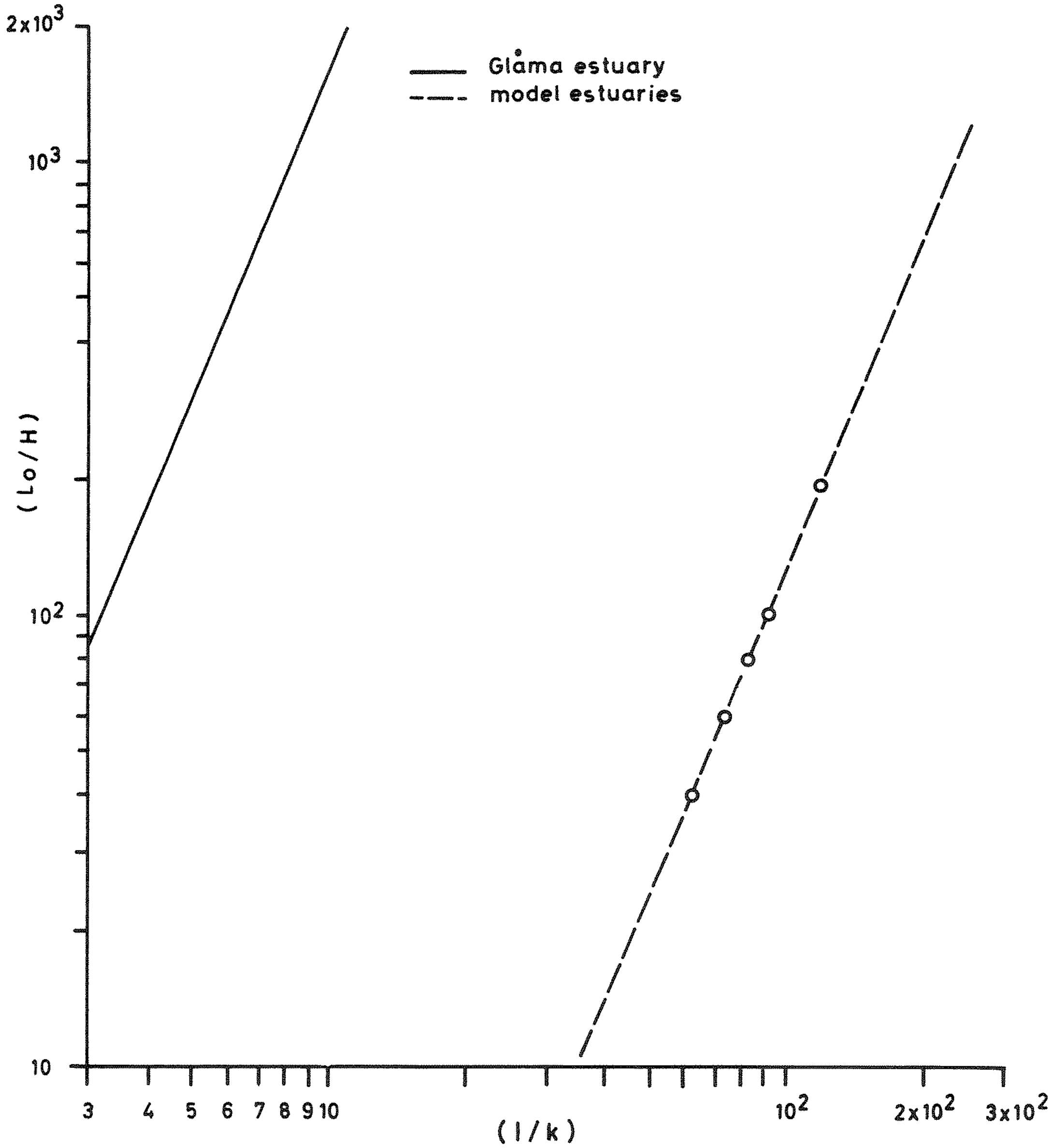

Fig. 10 (Lo/H) - (l/k) Relationship

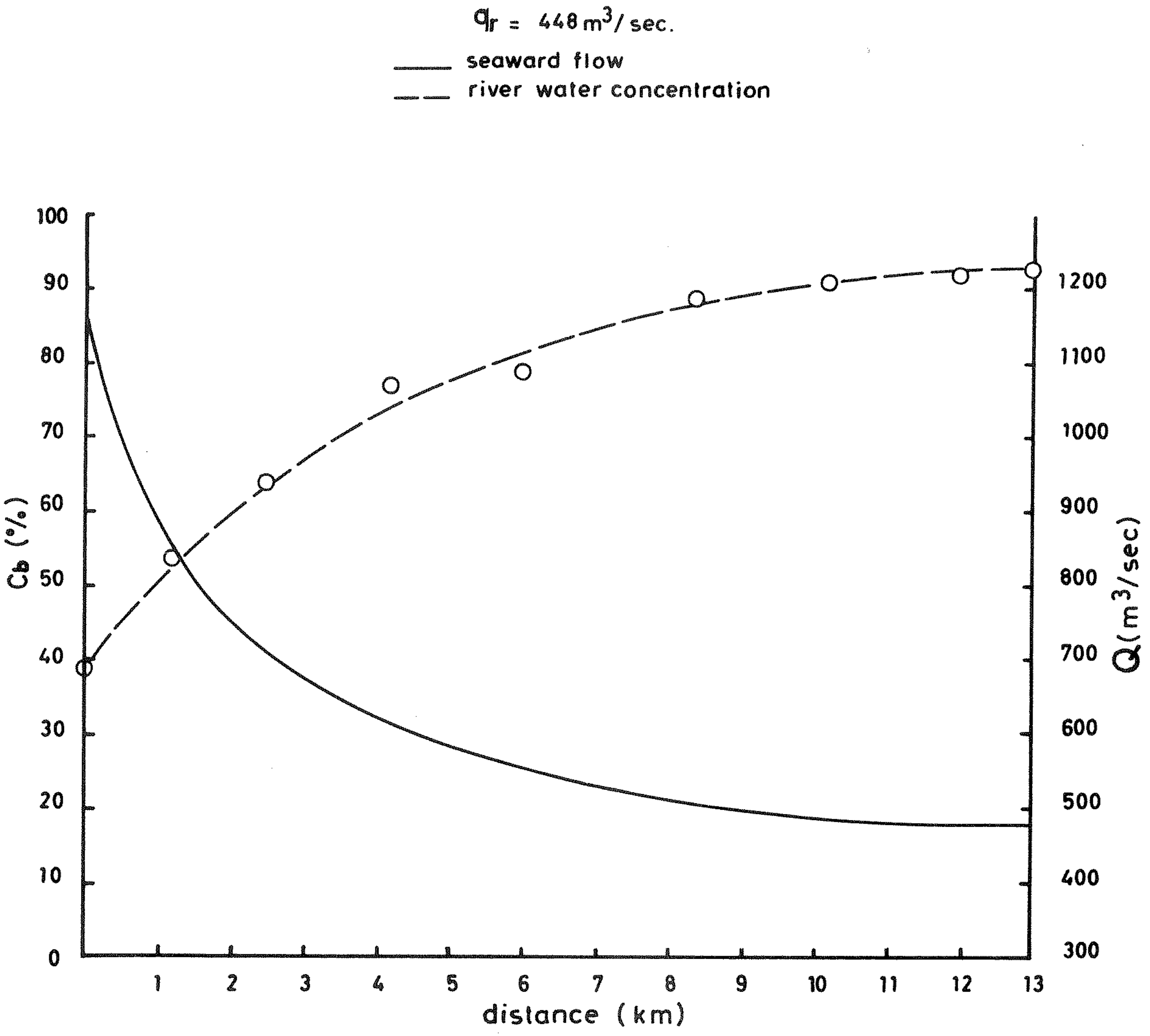

Fig. 11 Seaward flow of brackish water (seaw.+freshw.)