On the Change in Salinity Distribution and Bottom Topography after the Closing of the Mouth of Kojima Bay

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Abstract

The artificial construction of estuarine reservoirs strongly affects the salinity distribution, flow pattern and micro-topography in the water, and it is necessary for the effective utilization of water to investigate the change of salinity distribution in these reservoirs.

As an example of the surveys of estuarine reservoirs, many observations have been carried on in Lake Kojima and the adjacent sea over the ten years after the closing of the estuarine mouth.

The main purposes of this paper are, on the basis of data observed in Lake Kojima and the adjacent sea, to describe the effect of certain dominant factors on the exchange of water and to illustrate the change in the salinity distribution with reference to the salt balance calculation and to show the change in the bottom topography caused by the embankment.

Introduction

For the dual purpose of utilizing water in reclaimed lands or coastal urban areas and protecting estuarine regions from being damaged by tsunami or high tide, the artificial construction of estuarine reservoirs by closing the river mouth or estuarine outlet has recently been planned in Japan.

In general, the construction of estuarine reservoirs brings about marked changes in the hydrological conditions and much care must be taken about the rapid change in water quality and bottom topography, for effective utilization of water and reasonable prevention of topographic disasters.

The change in the salinity distribution after the closing of the outlet seems to be an interesting problem not only for a water supply engineer but also for an estuarine oceanographer, as a model case of the bar-built type estuary in a nonsteady state.

Many observations have been carried on in Lake Kojima and the adjacent sea, in southern Okayama Prefecture along the Seto Inland Sea. It was constructed in 1956 by enclosing a part of Kojima Bay with a long dyke and is the first of its kind in Japan. The general view of Lake Kojima and arrangement of observation points are shown in Fig. 1.

On the basis of observation, theoretical and experimental analyses were carried out for the purpose of studying the exchange of fresh and salt water and the calculation of the salt balance and the estimation of the salinity distribution in future were made. Furthermore, the effects of the embankment on the micro-topography were examined from sounding data.

This paper describes the important results of these analyses investigating the physical process of salinity change in time and space and the topographic change in the bottom.

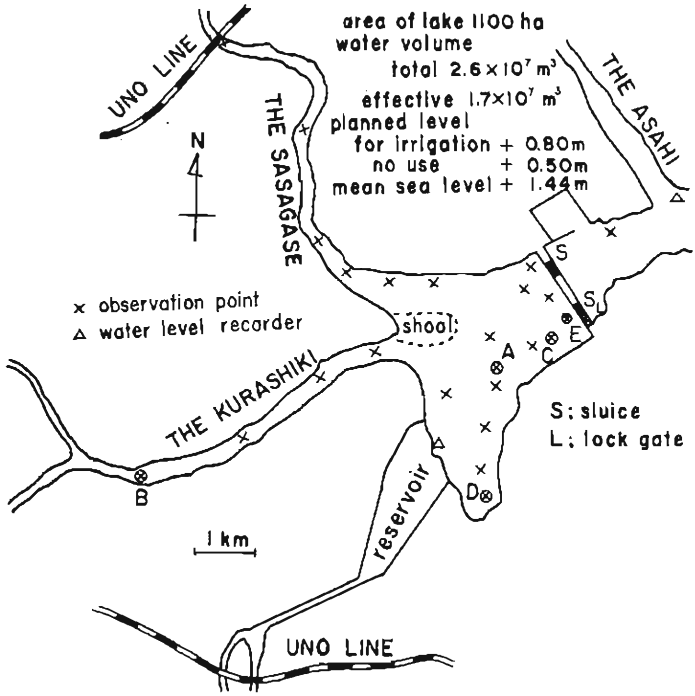

Fig. 1 General view of Lake Kojima

1. Dominant factors controlling the exchange of fresh and salt water.

(i) Fresh water inflow

By the term fresh water inflow, we define the total amount of inflow into the lake from rivers and land and precipitation on the water surface after subtracting both the amount of evaporation from the surface and an amount drawn up for utilization of water.

After the closing of bay mouth, the fresh water inflow rate may be estimated using water level records and the surface area of the lake, while before closing some estimation must be made for the individual components mentioned above.

(ii) Capacity of the lake

In general the capacity of the lake i.e. the volume of water kept in store, may vary from time to time, but the variation is expected to be so small owing to gate control that we may use mean values which are kept constant through both the two periods— summer (irrigation) period and the remaining period.

An essential factor in the exchange is neither fresh water inflow nor lake capacity, but the ratio of these factors. The larger the ratio (fresh water inflow/capacity of the lake), the more rapidly the exchange proceeds.

(iii) Turbulent mixing

Since the inflowing fresh water is lighter than the salt water pre-existing in the lake, it flows at the surface layer, mixing, to some extent, with the underlying salt water and flows out to the sea through sluices.

In this way the salt water in the lake is gradually replaced by fresh water and the exchange rate depends primarily on the degree of turbulent mixing between the two types of water.

After closing, tidal mixing can be ignored and fluctuations in water level owing to sluice gate control range in amplitude from several cm, to 20 or 30 cm, and therefore turbulent mixing will become much smaller than before closing.

The results of analytical calculation based on the salinity change and experiments on dye patch dilution by the author show that the coefficients of turbulent diffusion are about 10^4 and 10^{-2} (c. g. s.) in the horizontal and vertical directions, respectively.

With such weak mixing action, stable density stratification occurred in the lake and controlled the exchange rate.

(iv) Intrusion of salt into the lake water after closing

Causes of intrusion of salt after closing are summarized as follows :

(a) sea water intrusion through gates and dyke.
(b) sea water intrusion through lock gates accompanied by ship passage.
(c) brackish water inflow from polder land around the lake.
(d) salt inflow by diffusion process from bottom sediment.

We can control causes (a) and (b) as strictly as possible by good construction and reasonable operation, and can partly control cause (c) with proper planning for irrigation and drainage, but can do nothing about cause (d).

The estimated amounts of salt due to the above mentioned causes are later shown separately in the analysis of the salt balance.

(v) Bottom topography

The bottom topography of the lake, which was partly determined by the artificial construction of dyke and gates, influences the density stratification and flow pattern and therefore controls the exchange rate.

The effect of hollows on the bottom trapping salt water is shown later with figures.

(vi) Effect of the Coriolis force

In general the Coriolis force tends to result in a unique lateral salinity distribution in large scale estuary [1]; salinity on the right-side is lower than that on the left side of the estuary at the same level.

However, the results observed have shown no such character and in considering a small scale lake we may leave out the Coriolis force as a factor.

2. Salinity decrease after closing

A basic balance equation for the mean salinity S, in the lake, is expressed by

$$\frac{dS}{dt} = \frac{1}{V}(I-O) \qquad (1),$$

where t : time, V: capacity of the lake.
I : inflow rate of salt entering the lake.
O: outflow rate of salt leaving the lake.

The items comprising I are described in **1** (iv) and the estimation of each item is shown later, but for simplicity it is expressed by

$$I = S_{in}\, Q_{in} \qquad (2),$$

where Q_{in} : inflow rate of water,
S_{in} : mean salinity of the inflow water,

Outflow rate of salt is also expressed by a similar form as follows

$$O = S_{out}\ Q_{out} \quad \cdots\cdots (3),$$

where Q_{out} : outflow rate of water, (through sluice gates)
S_{out} : mean salinity of the outflow water.

Since the water level is supposed to be kept nearly constant after closing, we may assume for the exchange period that

$$Q_{in} = Q_{out} = Q \quad \cdots\cdots (4),$$

For the same period, S_{in} is assumed constant a for simplified analysis

$$S_{in} = a \quad \cdots\cdots (5),$$

In order to solve eq. (1), we further need information about a functional form of S_{out}.

Although Jansen [2] assumed a linear relation $S_{out}=rS$ (r : a constant coef.), this assumption is somewhat unreasonable, since the predominant effect of the density stratification has not been taken into account there.

The density difference between inflow water and pre-existing water is proportional to $(S-a)$, and the larger this difference is, the more stable the density stratification is and the less mixing occurs between the two types of water.

Therefore, the larger $(S-a)$, the smaller S_{out}/S because the surface layer flow reaches the sluice gate picking up a smaller amount of salt from the lower salt water.

Taking such process into account, the most simplified expression of S_{out} is given by

$$S_{out} = \{1 - K\ (S-a)\}\ S \quad \cdots\cdots (6)$$

Physical consideration of this expression is described in reference [3] and a different expression for S_{out} must be used in the case of special gate control for salt water exclusion (for example, partly opening gates and passing out only brackish water), but in the case of normal gate control at Lake Kojima, relation (6) holds with good approximation.

With the above expressions and the initial condition $S=S_o$ at $t=0$, the solution of eq. (1) is given as follows

$$S = \left(\frac{C}{K} - ae^{PQt/V}\right) / \left(C - e^{PQt/V}\right), \quad \cdots\cdots (7)$$

where $P = 1-Ka$, $C = (KS_o-Ka)/(KS_o-1)$.

Jansen's solution for the present case $(S_{in}=a)$ with $S_{out}=rS$ is given by

$$S = \frac{a}{r} + \left(S_o - \frac{a}{r}\right) e^{-rQt/V} \quad \cdots\cdots (8)$$

On the basis of observations of Lake Kojima, we take $a=0.2‰$, and $S_o=8.0‰$, and specify the parameter K to $0.12/‰$ by curve fitting.

The salinity decrease over about 100 days after the closing of the outlet is shown in Fig. 2 (A) and theoretical curves according to eq. (7) with the above parameters and eq. (8) with $r=0.3$ are drawn in the same figure.

Eq. (7) expresses the tendency of salinity change much better than Eq. (8) and this means that density stratification controls the mixing process and the exchange rate.

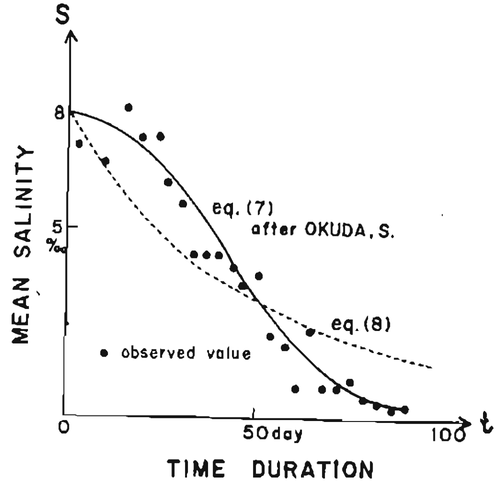

Fig. 2 (A) Salinity decrease immediately after the closing of the outlet

The model experiments on a large scale which were carried out in 1967 by Nakano-umi Reclamation Office for the planning of the enclosure of Nakano-umi, show the effect of the density stratification on the decreasing rate of salinity after the construction of the embankment and the results verify the good applicability of eq. (7) to salinity change.

3. Salinity Distribution

Periodical observations of salinity in the lake were carried out at fixed points, shown in Fig. 1 and some of the results are shown in Fig. 2.

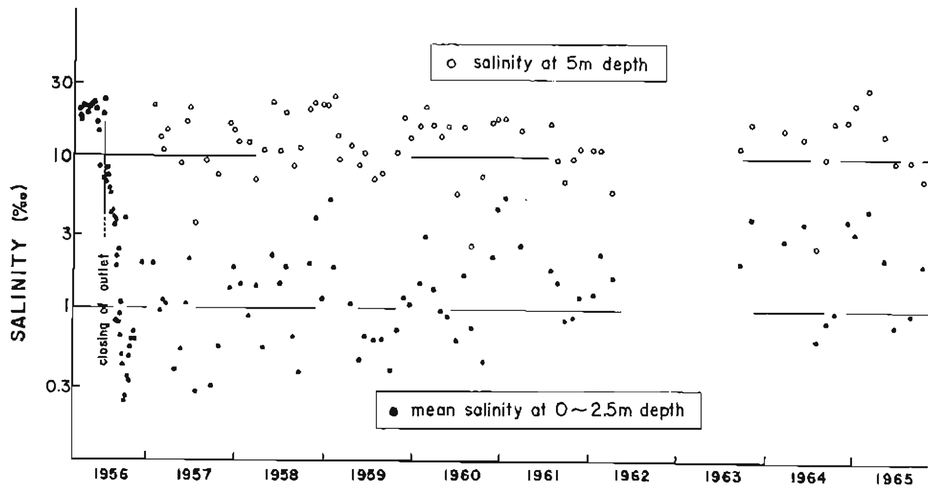

Fig. 2 (B) Salinity variation over the 10 years after closing (semi-log scale)

Salinity observations were carried out at 50 cm depth intervals, but Fig. 2 (B) gives two kind of data——one (•) is the average value for depths of 0~2.5 m corresponding to the layer for irrigation use, and (◦) is the value at a depth of 5 m corresponding to the hollow bottom of the lake.

Fig. 2 (B) shows that an irregular seasonal variation in the average salinity has continued for a long period after the rapid decrease in the period of exchange between fresh and salt waters while the 5m-salinity was not changed so much as the average salinity by closing.

This shows the stable existence of salt water in the hollow of the lake without strong mixing between fresh and salt waters.

Fig. 3 shows a few examples of salinity distribution observed in the lake.

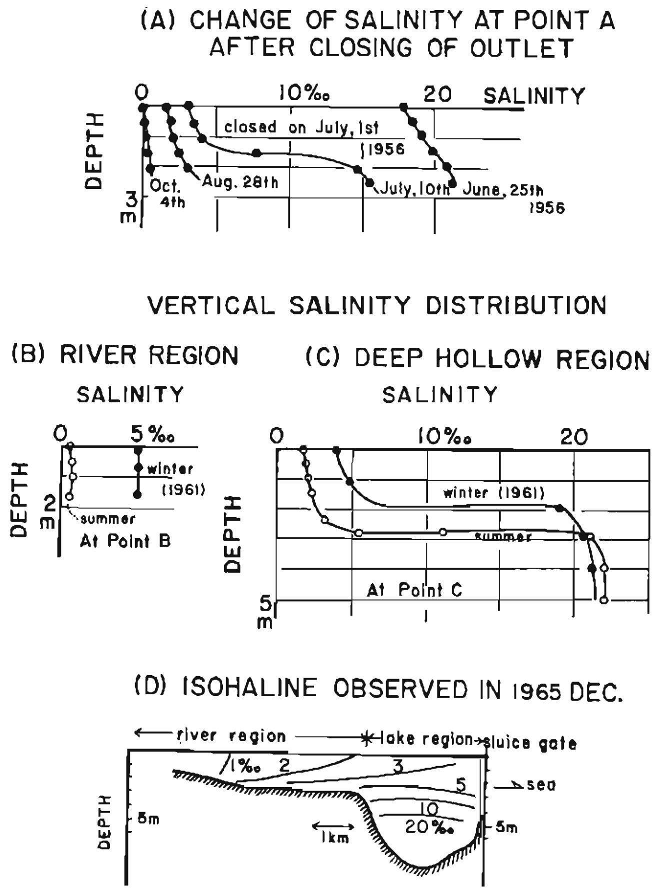

Fig. 3 Salinity distribution in the lake

Fig. 3 (A) shows the change in vertical salinity distribution at the center of (point A) the lake caused by closing.

Fig. 3 (B), (C) shows the seasonal change in the salinity distribution in the river region (point B) and deep hollow region (point C).

Fig. 3 (D) shows the recent salinity distribution along the vertical and longitudinal section.

These distributions indicate that stable density stratification appears after closing except in shallow and low salinity regions.

In general, as shown in Fig. 3 (D), the salinity distribution is vertically homogeneous in the upper stream region, horizontally stratified in the deep lake region and in an intermediate state in the boundary region.

(i) Salinity distribution in the river region

In the river region, salinity increase is approximately linear as the water flows down along the river course, and the longitudinal salinity distribution is derived from a diffusion equation in the next form [4].

$$S = \frac{(S_l - bl)(e^{ax}-1)}{(e^{al}-1)} + bx$$

where $a = U/D_l$, $b = \frac{P}{AU} = \frac{P}{Q}$,

here S : the salinity at the distance x from the upper limit of the river
S_l : the salinity at the outlet of the river
= the salinity of the lake surface
l : the length of the river course
U : the mean flow velocity
D_l : the longitudinal diffusion coefficient
A : the mean cross section area
Q : the mean flow rate
P : the amount of salt carried into the river per unit length of river, per unit time

Using the curve fitting method, the values of D_l, and P were determined as $D_l \fallingdotseq 2\times10^4$ cm²/sec, $P=2\times10^{-3}$ gr/cm sec.

The dye patch method using uranine solution gave the same order value for D_l.

(ii) Salinity distribution in the lake region

In the lake region, there exists a stable interface zone between surface river water and lower sea water.

This interface zone can be recognized by the vertical salinity distribution or more directly by an aqualung survey which shows a very sharp difference of temperature and suspended matter between surface and bottom water.

The position of the interface zone is not kept at a constant level but changes with time under various physical conditions.

The sea water intruding through gates and dyke pushes up the interface and the drawing out of sea water by gate control pushes down the interface, and therefore the height of the interface zone changes about 20～40 cm between after and before gate opening, but its mean height stays nearly equal to the height of the sill of the sluice.

Strong wind changes the state of the interface zone through two physical processes —— one is a drift current which brings about the inclination of the interface plane and the other is a vertical mixing which blurs the interface at first and pulls up the sea water to the surface layer.

The effect of the drift current was observed once at Point E by the author with continuous recording by electric conductivity.

The result shows that the change in thickness of the lower layer caused by the inclination of the interface reached about 50 cm in the case of a wind of 6～8m/sec.

The effect of wind mixing was also observed at Point E, but it is so dangerous to make observations from a small boat in a strong wind, that we observed the salinity distribution only before and after the blowing period of a strong wind and compared the two states. An example of the mixing effect caused by a strong wind of 8 m/sec is given in Fig. 4 and we can see the stable interface existing immediately after the strong wind blew.

Besides the strong wind, the state of the interface may be affected by a flood inflow from a river with a strong mixing action.

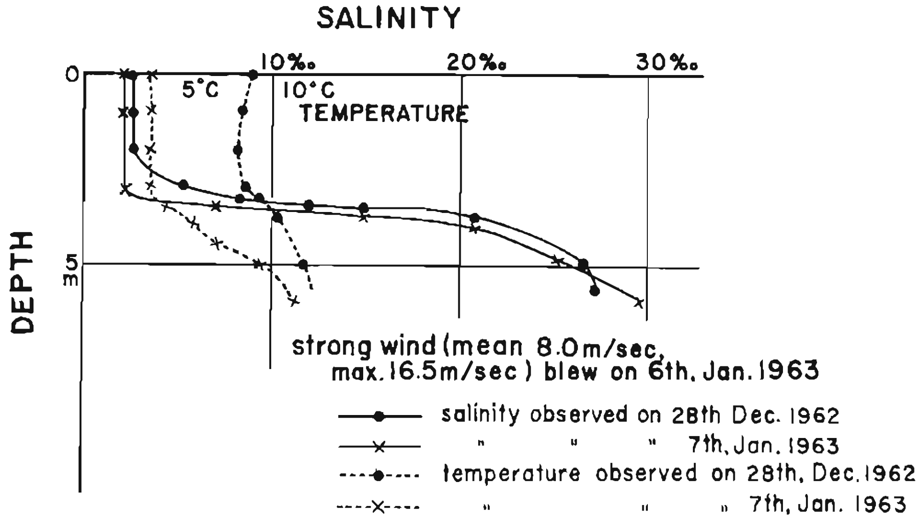

Fig. 4 Wind effect on salinity distribution

An example of such a mixing effect is shown in Fig. 5. The flood inflow of 60~80 m^3/sec from rivers for the period 21~24th Apr. 1957 seemed to push out the salt water from the hollow, but intruding sea water stored up again in the hollow.

There is such a small number of observations of the change in the interface state that a quantitative analysis can not be carried out at the present stage.

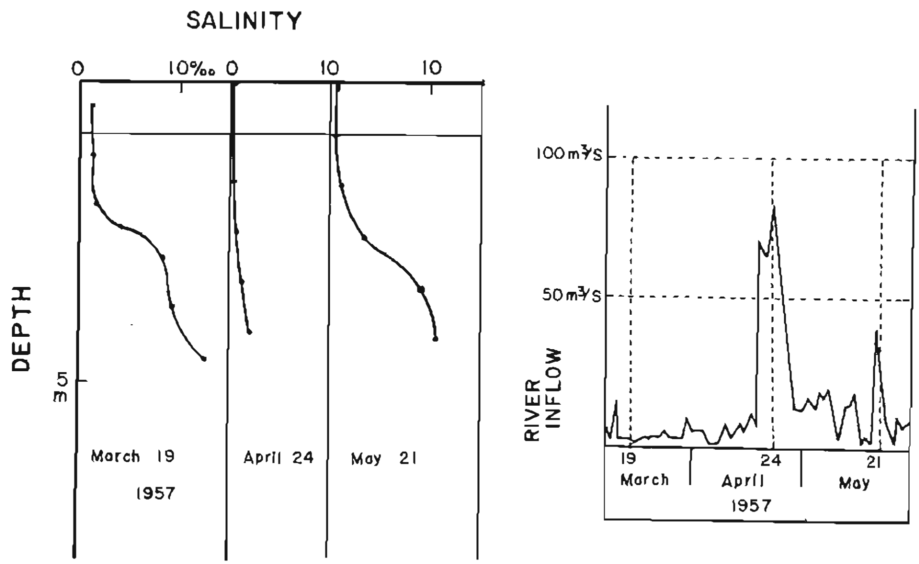

Fig. 5 Flood inflow effect on salinity distribution

4. Salt Balance

For effective utilization of water, it is very important to estimate the mean value and variation of salinity in the lake, and a salt balance survey was carried out over a few specified periods.

The amounts of the incoming items of the salt balance described in **1** (iv) (a), (b), (c), (d) were estimated as follows.

(a) The amount of sea salt intrusion through gates and dyke can be estimated by exact observation of the salinity distribution of sea water stored in the hollow near the dyke.

(b) The amount of salt intruding through lock gates can be estimated from the volume of sea water between the two gate doors, salinity of the water and the frequency of gate opening.

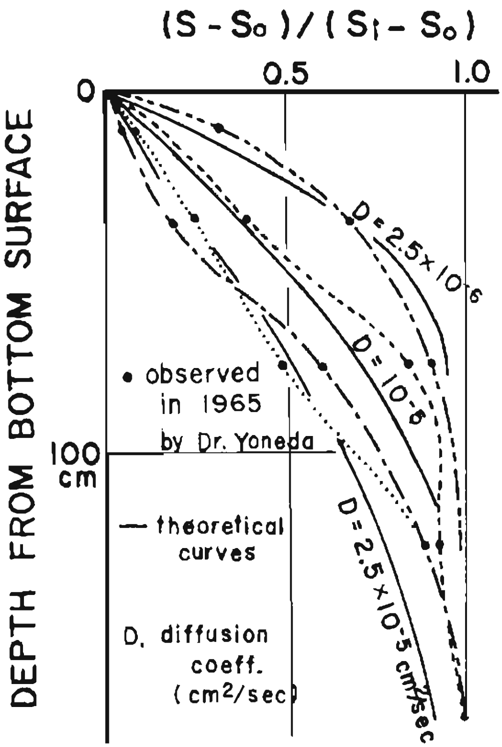

Fig. 6 Vertical distribution of salinity in bottom soil

(c) The amount of salt inflowing from polder lands can be estimated from the product of the inflow rate of brackish water and its salinity, which were measured at pumping stations over a specified period.

(d) The amount of salt released from the bottom soil can be estimated from the salinity distribution in the ground water through bottom soil. From the lake bottom, pieces of soil were sampled with an auger, and after extracting the water from the soil, the salinity in the water was measured.

A vertical distribution of salinity through the bottom soil layer is shown in Fig. 6.

The salt supplying rate per unit area per unit time is derived from the diffusion equation by the following,

$$nD\left(\frac{\partial S}{\partial Z}\right)=n\sqrt{\frac{D}{\pi t}}(S_i-S_o)\cdots(9)$$

where n : porosity,
D : diffusion coefficient
S_i : initial salinity through bed soil
S_o : bottom surface salinity
Z : depth from bottom surface
t : time duration after water exchange.

Diffusion coefficient D is determined using curve fitting as shown in the same figure.

(e) The outgoing item of the salt balance consists only of the outflow of salt through open sluice gates to the sea, and its amount can be estimated as the product of the outflow rate of water and its mean salinity.

But owing to density stratification near the gate, the measurement of the outflow current and salinity needs special care.

Some of the results of salt balance analysis are given in table 1.

Table 1 Salt Balance in Lake Kojima

Incoming	1965 Mar. 3—May 7	1965 June 24—Aug. 28
(a) salt intruding through gates and dyke	102.4×10³ton	59.6×10³ton
(b) salt intruding through lock gates	5.4 〃	3.1 〃
(c) salt inflowing from polder lands	0.5 〃	22.6 〃
(d) salt inflowing from bottom soil	+) 0.4 〃	0.4 〃
(e) total incoming	108.7 〃	85.7 〃
Outgoing		
(f) salt outgoing through gates	182.2 〃	83.6 〃
(g) increase of salt stored in the lake (e)−(f)	−73.5×10³ ton	+ 2.1×10³ ton

This table shows that the amounts of each item are not constant, but change with time.

For example, in winter, the amount of sea water intrusion through gates and dyke increases because of the lowering of the lake water level, and in summer, the amount of brackish water inflow from polder land increases because of the pumping up of irrigation water for the polder lands.

The amount of salt inflow from the bottom soil seems to be negligible in recent times, but it is supposed that immediately after closing it exceeded the recent inflow rate by about ten times or more, because, from eq. (9) the inflow rate is inversely proportional to $\sqrt{t}$ and the mean value of D was larger at the bottom surface layer in a loose packing state than the deeper layer, and there was an active movement of underground water which brought out a larger value of D than that in the motionless state.

Although the amount of intruding sea water is very large, the salinity of the upper water layer from which the irrigation water is pumped up is not so high, owing to the sinking down of heavier sea water along the hollow bottom.

Considering the physical characteristic of each item of the salt balance it seems that the present state of salinity distribution will continue for the time being without any remarkable change.

However, there still remains the danger of high salinity damage to rice production (limit of salinity concentration 3‰) under especially unfavourable conditions —— for example, strong wind mixing after a long spell of dry weather.

Under such conditions, a thin surface layer of fresh water may break up and the salinity even in the upper layer máy increase promptly over the permissible limit.

5. Change in Bottom Topography

As the embankment for the enclosure of the lake stops the sea water intruding into the inner end of the bay, the tidal current outside the dyke becomes weaker, and the flow pattern changes after construction of the bank.

Therefore, the embankment will bring about a rapid change in the bottom topography of the adjacent sea, and it is very important to estimate that change beforehand at the planning stage of the embankment.

A theoretical law was derived by Bruun and Gerritsen [5] for the relation between the crosssectional area A of an estuarine mouth and the tidal prism Ω which represents the total amount of water that flows into the estuary during one flood period.

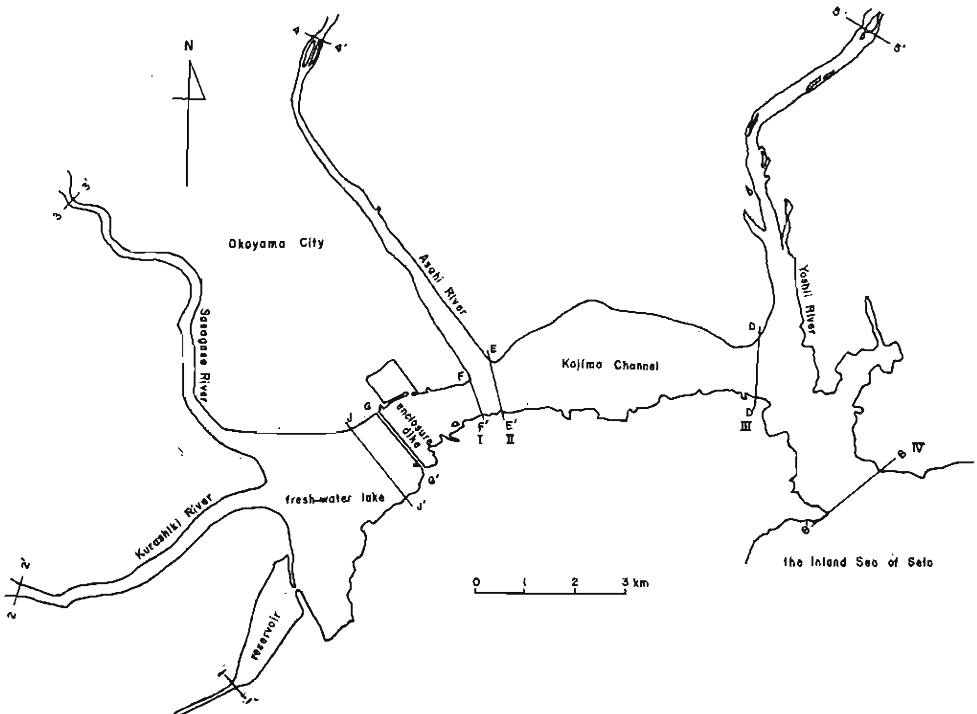

Fig. 7 Sounding lines for the survey of bottom topograpby—I, II, III, IV
The limits of tidal effect —1, 2, 3, 4, 5

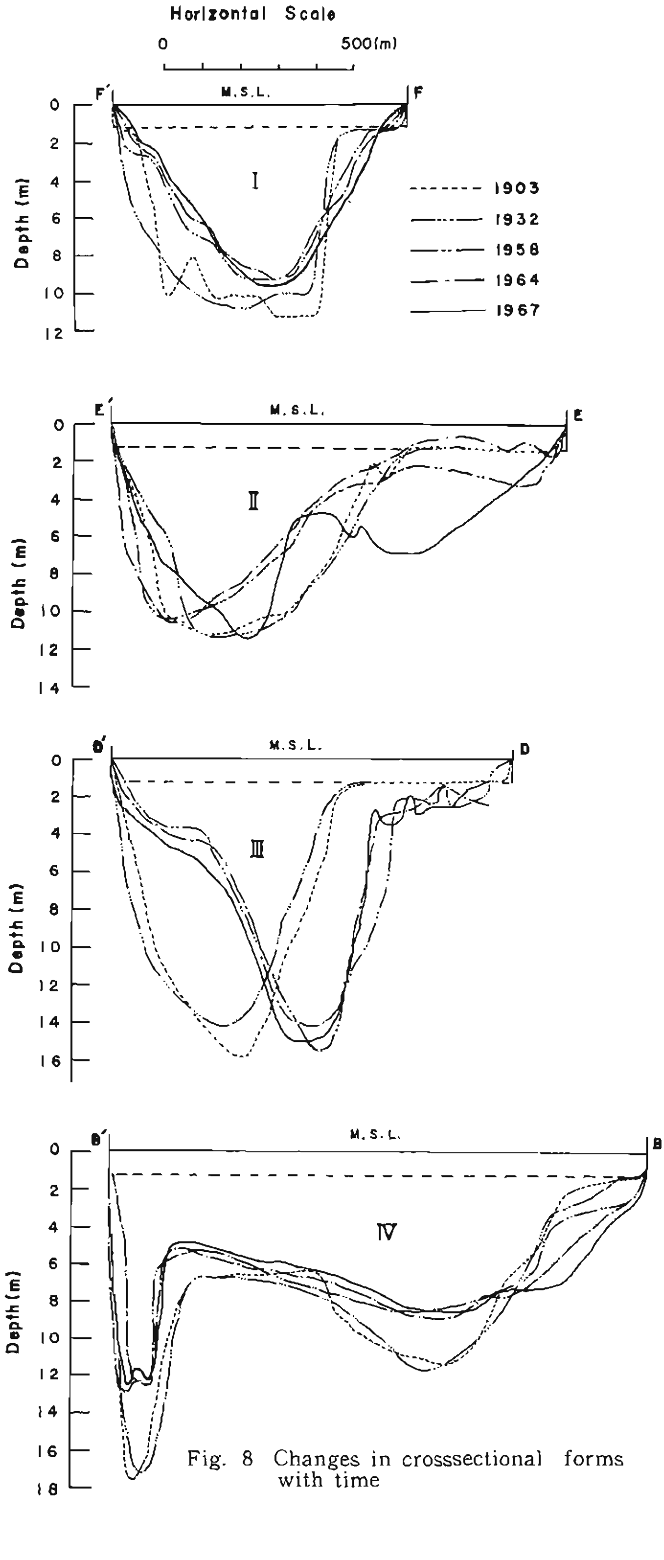

Fig. 8 Changes in crosssectional forms with time

Their" Gorge Theory" shows the linear relation $\Omega = \text{const} \cdot A$ and verifies the statistical relationship with the real values of Ω and A in various inlets.

This theory predicts that the decrease in the tidal prism caused by the embankment brings about a direct decrease in the crosssectional area at the adjacent bay, that is, rapid filling up with sand or mud outside the dyke.

In order to test the applicability of this theory to the change in the bottom topography of Kojima Bay caused by the embankment, crosssections of Kojima Bay at the positions shown in Fig. 7 were investigated from the results of soundings in the past (1903, 1932, 1958, 1964) and recent soundings by the author (1967).

The crosssectional forms are shown in Fig. 8 and the crosssectional areas are given in Table 2 with the tidal prism through each section.

Table 2 Crosssectional Area and Tidal Prism in Kojima Bay

		Section I	Section II	Section III	Section IV
Mean Crosssectional Area before embankment	A_b	$4.3\times10^3 m^2$	$4.8\times10^3 m^2$	$5.4\times10^3 m^2$	$9.2\times10^3 m^2$
Mean Crosssectional Area after embankment	A_a	$3.4\times10^3 m^2$	$5.1\times10^3 m^2$	$5.6\times10^3 m^2$	$8.6\times10^3 m^2$
A_a / A_b		0.79	1.06	1.04	0.93
Tidal Prism before embankment	Ω_b	$14.2\times10^7 m^3$	$16.4\times10^7 m^3$	$24.1\times10^7 m^3$	$32.1\times10^7 m^3$
Tidal Prism after embankment	Ω_a	$2.2\times10^7 m^3$	$4.3\times10^7 m^3$	$12.1\times10^7 m^3$	$20.1\times10^7 m^3$
Ω_a / Ω_b		0.16	0.26	0.50	0.63

A comparison of the ratios Ω_a/Ω_b and A_a/A_b shows that the changes in the crosssectional areas are small in spite of the large decrease in the tidal prism, and that no linear relation exists between Ω and A.

The changes in A with time are shown in Fig. 9 and imply that small irregular fluctuations independent of the large change in Ω seem to exist.

The cause of the fluctuations must be investigated from the local survey of erosional and depositional conditions with reference to the local flow patterns. But, considering the remarkable changes in the crosssectional forms with small changes in crosssectional areas and the wide distribution of river sand in Kojima Bay, it seems that the bottom topography in this region is mainly controlled by river floods from the Asahi and Yoshii, especially with the bed load transport at flood stages.

Therefore, at most estuaries in Japan similar to Kojima Bay, where the effects of river flood on the bottm topography seem to be more dominant than that of tidal current, the topographic change can not be estimated by the Gorge Theory, but must be investigated from the river bed process during flood periods.

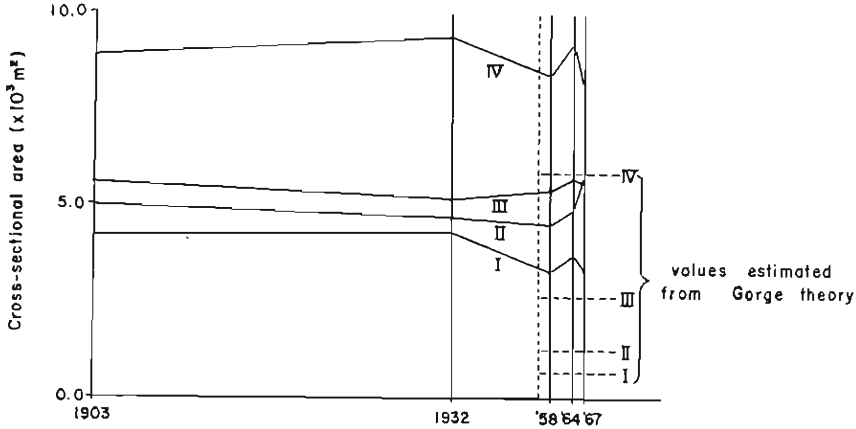

Fig. 9 Changes in crosssectional areas with time

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