

## SALT BALANCE IN KOJIMA LAKE

By

Setsuo OKUDA

(Received November 7, 1966)

### Abstract

The artificial constructions of estuarine reservoirs strongly effect the salinity distribution and flow pattern in the water, and it is necessary for the effective utilization of water to investigate the salt balance and salinity distribution in the reservoirs.

As an example of the surveys on estuarine reservoirs, the results of the observation in Kojima Lake were analysed on the basis of experimental and theoretical studies on the salt transport, in order to calculate the incoming and outgoing items of salt balance.

Furthermore, the salinity distribution in the river region where pumping stations for irrigation purpose are installed, was studied with regard to the salt supply from polder land and the horizontal diffusion in the river course, and a good agreement between theoretical and observed results was obtained.

### 1. Introduction

In recent years, the increasing demand for water supplies has required the artificial formation of estuarine reservoirs which are made by closing the river mouth or by constructing embankments in the adjacent sea area.

Typical forms of estuarine reservoirs being planned or constructed in Japan are shown in Fig. 1.

These reservoirs are constructed for the effective utili-

zation of water which would otherwise flow out wastefully to sea and they can supply fresh water to urban areas near the coast through short pipe lines.

Moreover, the closing of dams or banks is also useful in protecting estuarine regions from unusually high tide and tsunami.

The constructions of estuarine reservoirs bring about remarked changes of

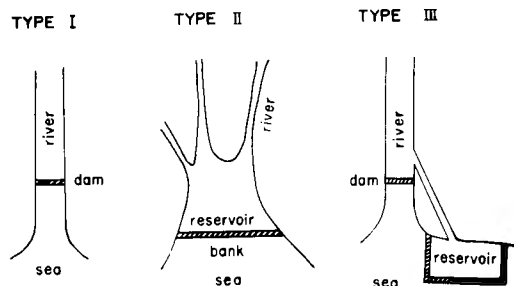


Fig. 1. Typical forms of estuarine reservoirs.

hydrological conditions and some important problems have to be studied prior to the construction in order to investigate the effects of the change.

These problems are as follows :

- (i) The estimation of salt balance in the closed water area in order to determine final salinity distribution.
- (ii) Study of the movement of fresh water discharged from the reservoir in relation to fishery productivity and scouring power to bed soil in the downstream region or the sea.
- (iii) A reasonable method of gate control for various river flow rates to prevent the rise of salt water or to admit the rapid passage of flood water.

This paper describes a study on the first problem which was carried out for the construction of Kojima Lake (Okayama Prefecture).

## 2. Salt balance in Kojima Lake

An analysis of the results obtained from observations on the salt balance in Kojima Lake is given in the following, together with some appropriate considerations.

A general view of Kojima Lake is shown in Fig. 2.

The lake was closed at the mouth of the estuary by a bank of about 2 km in length in August, 1956 in order to supply the polder lands around the lake with irrigation water.

Periodical observations of salinity were carried out at fixed points, shown

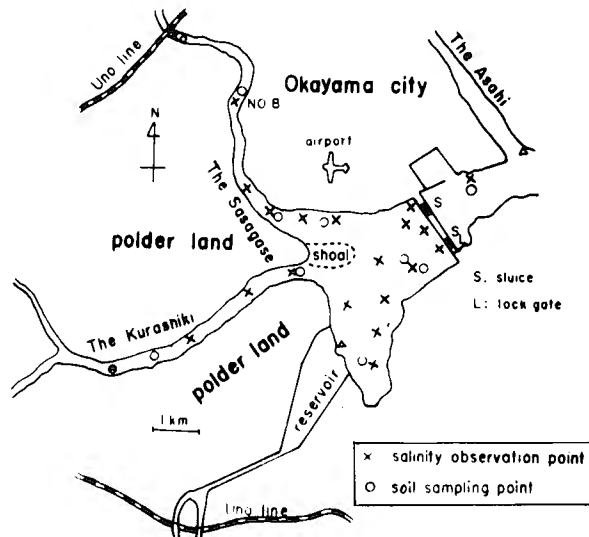


Fig. 2. General view of Kojima Lake.

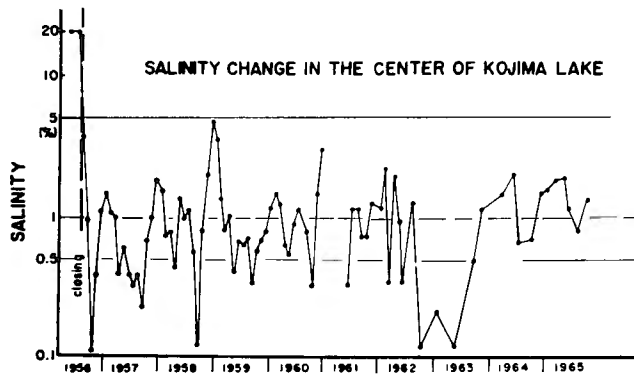


Fig. 3. Salinity change in the center of Kojima Lake.

by a cross (×) at every 50 cm depth interval, and soil samplings were carried out several times at the points shown by small circle (○). The decrease in average salinity in the center of the lake is shown in Fig. 3.

The curve shows a rapid decrease in salinity immediately after the closure and irregular change after that period.

The rapidly decreasing rate of salinity has already been analysed by the author (Okuda (1960)) in regard to density stratification and a better agreement between the analytical solution and observed values was obtained than by Jansen's method which disregards density stratification.

But here the results of the salt balance after a sufficient period of time has

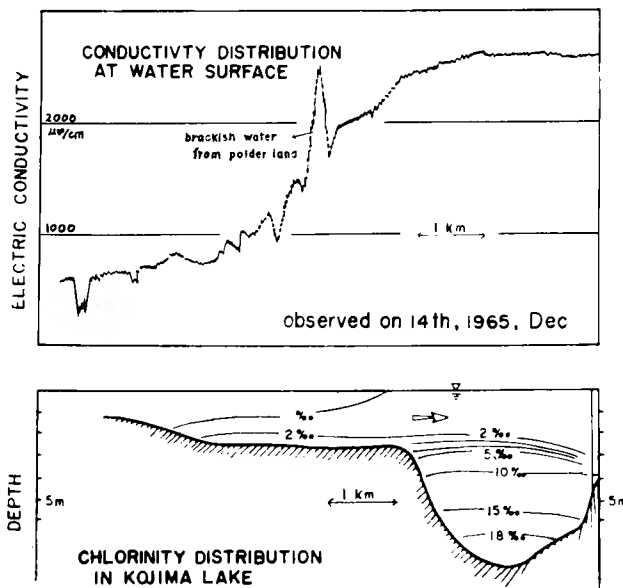


Fig. 4. Salinity distribution in Kojima Lake.

elapsed subsequent to the closure will be shown and some analyses of the final distribution of salinity in the lake will be described.

The recent distribution of salinity in the lake is shown in Fig. 4.

The upper part of the figure shows the distribution of electric conductivity on the water surface as determined by a recorder in a motor boat running on a fixed course. This curve shows that conductivity keeps an almost constant value in the lake region and changes promptly at the mouth of the river and decreases linearly upstream. The inflow of brackish water from the polder land brings about a local increase in conductivity.

The lower part of the figure shows the vertical distribution of chlorinity in both river and lake regions. The high chlorinity region is found in a concave depression near the closing bank and over that region a sharp interface exists between the lower salt water and the upper fresh water owing to the stabilizing effect of density stratification.

For irrigation, especially for rice production, the salinity of water must not exceed 3‰ and so it is very important to estimate the final maximum value of salinity in the upper water layer for the irrigation period. Therefore, we have to investigate some dominant factors controlling the salt balance in the lake water.

As a sample of investigation, the sheet-balance items for salt produced over a period of exact survey are listed in Table 1.

Table 1. Balance sheet for salt in Kojima Lake  
(period : 1964, June 12–July, 30)

incoming	
(i) sea water intrusion through gates and bank	$76.0 \times 10^3$ ton
(ii) brackish water from polder land	$9.2 \times 10^3$ ton
(iii) sea water through lock gates	$2.3 \times 10^3$ ton
(iv) salt from bottom soil	$0.9 \times 10^3$ ton (+
	<u><math>88.4 \times 10^3</math> ton</u>
outgoing	
outflow through gates with upper layer water	$177.0 \times 10^3$ ton (-
amount of salt stored in the lake	<u><math>-88.6 \times 10^3</math> ton</u>
amount of salt stored in the lake calculated from salinity distribution	<u><math>-91.3 \times 10^3</math> ton</u>

The largest inflow is the sea water coming through the gates and bank and its quantity was estimated by two methods independent of each other.

Direct measurements of the flow current and section area at leak holes obtained by aqua-lung diving, give the flow rate of sea water and its rate is proportional to the square root of the level difference between the sea and lake.

Then, from the diving survey and continuous observation of sea water salinity and the water level difference, the incoming of salt for a given period can easily be estimated.

Another method for estimating the salt intrusion is to observe exactly the salinity distribution in the depression near the gates and bank where other in-comings of salt are negligible, and to assess the total amount of salt stored in it. The difference in the total amount of salt before and after a time interval is equal to the amount of salt carried in during that interval by sea water intrusion.

The values obtained from the latter method are written in the table because the former method gives a smaller value than the latter owing to a weak inflow at many places for instance the seepage flow through banks which cannot be detected by a current meter.

The second largest inflow is the brackish water inflow from the polder lands around the lake. The incoming salt from polder lands is estimated from the product of the inflow rate of brackish water and its salinity, which were measured at pumping stations over a specified period.

The sea salt coming through the lock gate is estimated from the volume of sea water stored between the two gate doors, salinity of sea water and the frequency of the gate opening. It has already been shown by the author's model experiments (Okuda [1963]) and observations that salt and fresh waters can be completely interchanged through an open door within five minutes after opening.

The minor but continuous inflow is the salt released from bottom soil by the diffusion process, and to estimate it exactly is very difficult.

The ground soil of the lake bottom had contained sea water before the artificial closure of the estuary, and after the change-over from salt water to fresh water, the bottom soil continued to release the salt into the lake water by the diffusion process.

The diffusion process consists not only of molecular motion but also of

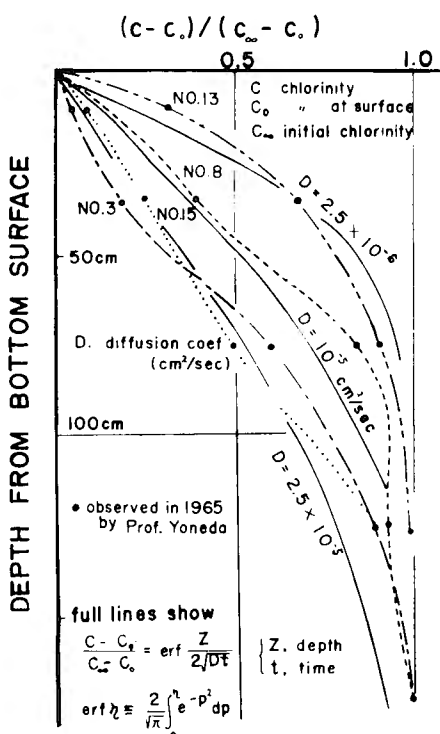


Fig. 5. Vertical distribution of chlorinity in ground water at lake bottom.

irregular fluid motion through the bottom ground, and so we can not estimate the amount of salt brought into the lake water solely by an experimental method using a small scale flume.

Therefore, in order to estimate its amount, the vertical salinity distribution in the underground water was investigated. From the lake bottom, soil pieces were sampled with an auger, and after extracting the water from the soil, chemical analysis was carried out by Prof. Yoneda at Okayama University.

A vertical distribution of salinity through the bottom soil layer at the present stage is shown in Fig. 5.

The salinity increases downward from the bottom surface and approaches the original value of sea water. Integrating the difference between present and original values of salinity from the bottom surface to a depth of layer still containing original sea water, we can estimate the amount of salt which has been transported from the lake bottom to the lake water for about nine years after the formation of the lake.

The transport rate depends on the physical character of bottom soil, and its average value for about nine years is estimated as  $2\sim 3 \times 10^{-3}$  mg/cm<sup>2</sup>·day.

The transport rate of salt at any given time through the bottom surface is shown as the product of the diffusion coefficient, the salinity gradient at bottom surface and porosity. The diffusion coefficient can be estimated by using the solution of the diffusion equation as shown in the figure. The solution was derived under the following two conditions: the initial concentration of salt in the underground water was constant  $C_{\infty}$  through the bottom soil, and the surface concentration of the lake bottom after closure was constant  $C_0$ . These conditions are satisfied approximately in the lake and so by comparing the observed salinity distribution with the curves from the theoretical solution, the approximate value of diffusion coefficient  $D$  can be determined. Its order ranges from  $10^{-6}$  to  $10^{-4}$  in the unit of cm<sup>2</sup>/sec.

The diffusion coefficient depends on the character of the bottom soil, but these figures seem to be much smaller than the figure  $10^{-3}$  cm<sup>2</sup>/sec obtained by our former calculation (Okuda [1962]) from the increasing rate of salinity along the river course two or three years after the closure.

This difference seems to indicate the heterogeneous structure of bottom soil, where a sedimentary deposit having higher porosity near the surface lies over the older deposit which has a denser packing, and so within the surface layer turbulent dispersion is dominant for the upward transport of salt, while in the deeper layer only molecular diffusion with small coefficient controls the transport of salt.

At the present stage, when the layer of decreasing salinity reaches to the

depth of 2 m from the surface, the mean value of the diffusion coefficient is roughly estimated to be  $10^{-5}$  cm<sup>2</sup>/sec. The figure written in the sheet-balance table was calculated as the product of the transport rate obtained by the above method, the effective bottom area of the lake, and the period of investigation.

On the other hand, the outgoing item of salt balance only consists of the outflow of salt through open sluice gates to the sea. 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.

The vertical distributions of the outflow current and salinity observed at a sluice gate are shown in the Fig. 6.

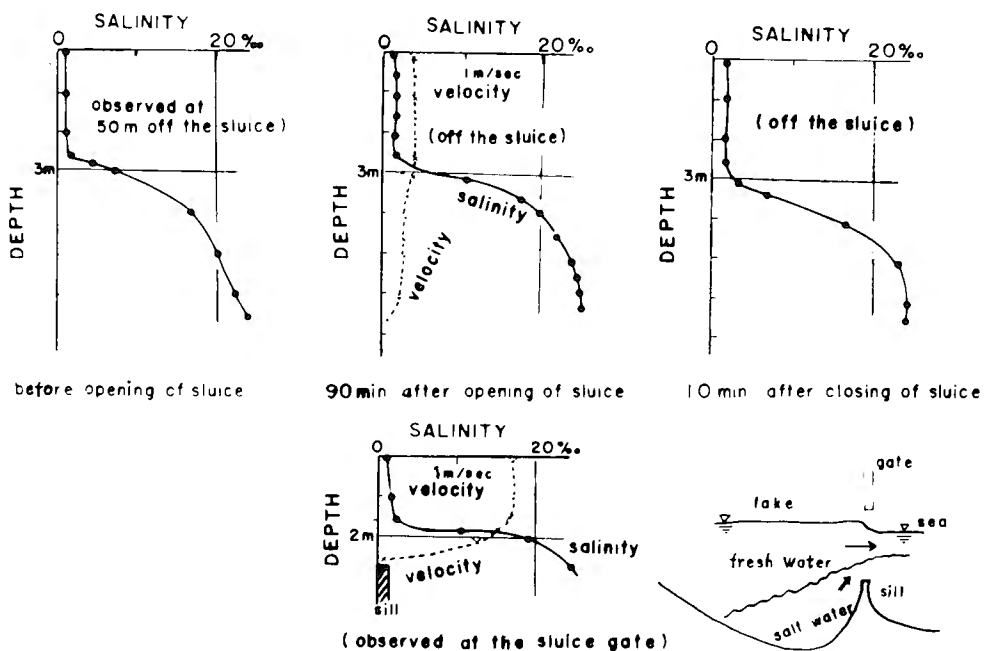


Fig. 6. Salinity and velocity distribution at the sluice gate.

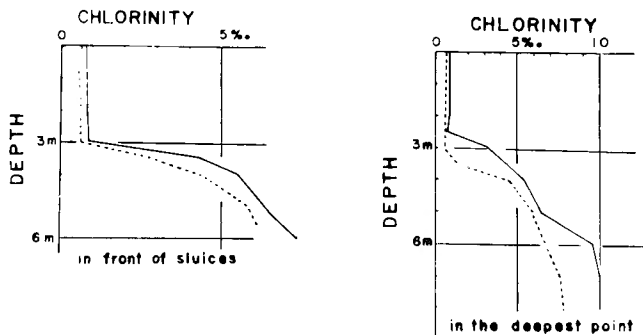
From these distribution curves we can calculate the pattern of outflow with density stratification and the inclination of interface between two waters as shown in the lower part of this figure. This pattern was confirmed by our model experiments (Okuda [1963]) which were carried out to show how the upper layer flow extracts out lower salt water through interfacial friction. From the piling-up effect of lower salt water and the inclination of interface as shown in the figure, the mean salinity of outflowing water becomes higher than that of upper layer water near the gate in a motionless state.

It is very difficult to estimate the outgoing salt owing to the variation of out-flow pattern which depends on the density stratification and control conditions of the gates. The figures in the balance-sheet show approximately an average value for an observed period.

The decrease of salt calculated from the difference between incoming and outgoing for the observation period was compared with that value obtained from the difference of the total amount of salt in the lake before and after the observation period, as shown in the table. There is a good agreement between the two values, but considering the large error inevitable in field observation taken over a wide area and for a long period, it is supposed that this agreement is rather accidental. However, the method of estimation for each term seems to be useful for the planning of estuarine reservoirs.

Apart from the salt balance, the vertical mixing of lake water by high wind has to be investigated carefully, for strong mixing may bring about high salinity in the upper layer of the lake.

It is so dangerous to make the observations from a small boat in a strong wind, that we observed the salinity distribution before and after the blowing period of a strong wind and compared the two states in order to investigate the mixing effects. An example of the mixing effect caused by a strong wind of 7~10 m/sec. is given in Fig. 7.



..... before wind blowing, on 15th, 1965, Dec.  
 — after wind blowing, on 17th, 1965, Dec.  
 Strong wind of 8~10 m/sec. blew on 16th  
 and wave height reached 50 cm.

Fig. 7. Wind effect on chlorinity distribution.

In this figure we can see that a slight increase of salinity in the upper layer occurs and the stable interface still exists after the strong wind has blown.

### 3. Salinity distribution in the river region

Pumping stations for irrigation are set along the rivers Sasagase and Kura-



shiki and it is very important to study the salinity distribution in the river region under various hydrological conditions.

The large incoming term in salt balance for the whole reservoir, for example, the sea water intrusion through the gates, bank and lock can not directly affect the salinity distribution in the river region because of the long distance from the intrusion point. Some results from the chemical analysis of river waters by the author (Okuda [1965]) show that there is little effect from sea salt on the river water and that the incoming salt from the groundwater of polder land and the river bed controls the salinity distribution in the river region. So some analytical studies were tried in order to express the salinity distribution quantitatively on account of the incoming salt.

In the steady inflow state in late autumn and winter, salinity distribution takes a stationary form, and salinity increases almost linearly with the flowing distance in the river except at the river mouth where a steep increase is found. The full line in Fig. 8 shows the mean salinity distribution averaged at Sasagase and Kurashiki rivers observed in the winters of 1963 and 1964.

For a stationary state where time rate of change is negligible, the longitudinal change of salinity along the river course is expressed in the following differential equation

$$U \frac{dS}{dx} = \frac{d}{dx} \left( D_H \frac{dS}{dx} \right) + \frac{P}{A},$$

where  $x$  is the longitudinal distance from the fixed boundary section between fresh and brackish waters, and salinity  $S$  depends on  $x$  in the region from  $x=0$  to  $x=l$  (river mouth),  $D_H$  is the horizontal diffusion coefficient and is assumed to be constant throughout the region for constant flow without tidal mixing, and  $P$  is the amount of salt carried into the river water per unit length of the river course per unit time,  $U$  is mean horizontal velocity and  $A$  is the mean cross section area of river and all these parameters are assumed to be constant for the steady state period.

The boundary conditions are given by the following equations based upon the observed results :

$$\begin{aligned} \text{at } x=0 & \text{ (upper limit of brackish zone), } S=0 \text{ (completely fresh)} \\ x=l & \text{ (the river mouth), } S=S_i \text{ (lake water salinity)} \end{aligned}$$

Then the solution of the above equation is obtained in the following form,

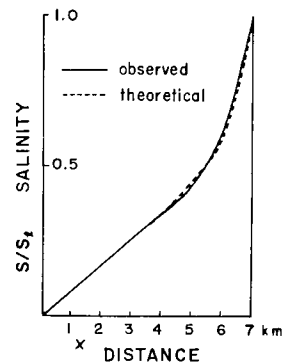


Fig. 8. Horizontal distribution of salinity in the river region.

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

where  $a \equiv \frac{U}{D_H}$  and  $b \equiv \frac{P}{AU} = \frac{P}{Q}$ ,

here  $Q$  means the flow rate  $UA$ . The plausible values of  $a$  and  $b$  corresponding to the observed curve in Fig. 8 can be determined by numerical trial and error methods.

The dashed line is drawn by the values of  $a = 1.5 \times 10^{-5}$ ,  $b = 8.6 \times 10^{-10}$  (in C.G.S. unit) and there is a good agreement between observed and theoretical distribution.

Using the mean values for the observed period

$$U = 0.25 \text{ cm/sec}, \quad Q = 2 \times 10^6 \text{ cm}^3/\text{sec},$$

the numerical values of  $D_H$  and  $P$  are determined as follows.

$$D_H = 1.7 \times 10^4 \text{ cm}^2/\text{sec}, \quad P = 1.9 \times 10^{-3} \text{ gr/cm sec.}$$

The dye patch method carried out near the river mouth gave the value of  $D_H = 1 \sim 5 \times 10^3 \text{ cm}^2/\text{sec}$  for the diffusion phenomena during a period of one hour and therefore the above value seems to be feasible for a longer time interval.

The total quantity of salt coming into the river region is obtained as the product of  $P$ , river length and period. For the convenience of comparison, if a 49 days period is taken, as in Table 1, the total salt income reaches  $5.8 \times 10^3$  ton. This value is smaller than the incoming term (ii)  $-9.2 \times 10^3$  ton, but taking into account the smaller subsurface inflow in winter compared with summer, it seems reasonable for an approximate estimation.

The comparison of the horizontal gradient of salinity in the river region under constant hydrological conditions observed every year shows a slow decrease in the salt income rate ( $P$ ) as time passes. It is supposed that the escaping of salt from polder land soil by irrigation will bring about a decrease in the supply to the river region.

### Acknowledgement

The author is indebted to Dr. S. Hayami, the former professor of Kyoto University for valuable advice and continuous encouragement, and to Dr. S. Matsubara, professor of Shimane Agricultural College, for kind help.

I also wish to express my thanks to Chugoku-Shikoku Regional Agricultural Office for generous assistance in field surveys.

### References

Okuda, S., 1960 ; The exchange of fresh and salt waters in the bay after closing the

- outlet. *Jour. Oceanogr. Soc. Japan*, 16, 7-14 (in Japanese).
- Okuda, S., 1962 ; The effect of released salt from the lake bottom on the salinity distribution in an estuary after the closing of outlet, *Jour. Oceanogr. Soc. Japan*, 18, 107-110.
- Okuda, S., 1963 ; Salt balance in Kojima Lake (Part 1), *Annuals Disaster Prevention Res. Inst. Kyoto Univ.*, No. 6, 189-196 (in Japanese).
- Okuda, S., 1965 ; Salinity decrease in estuarine reservoirs (Part IV), *Suion no Kenkyu (Study on Water Temperature)*, 9, No. 3, 7-10 (in Japanese).