Journal of Hydroscience and Hydraulic Engineering
Vol. 14, No. 2, November, 1996, 29-37 14.

FLOW OBSERVATION IN THE SEMI-ENCLOSED BAY OF A BRACKISH LAKE AND APPLICATION OF A FLOW SIMULATION MODEL

By

Shoji Fukuoka

Professor, Department of Civil and Environmental Engineering,
Hiroshima University, Higashi-Hiroshima, Japan

Naoya Matsumoto

Chugoku Regional Construction Bureau,
Ministry of Construction, naka-ku, Hiroshima, Japan

Isamu Mizoyama

Izumo Work Office, Chugoku Regional Construction Bureau,
Ministry of Construction, enya-arihara, Izumo, Japan

and

Nobuyuki Yamane

Osaka Office, CTI-Engineering Co., Ltd.,
Otemae, Chuo-ku, Osaka, Japan

SYNOPSIS

Flow observation was conducted with an Acoustic Doppler Current Profiler(ADCP) in a semi-enclosed bay of a brackish lake. Around the mouth of bay a circulation which had not previously been found was observed. During spring tide the water rotates in a clockwise direction and during neap tide in a counterclockwise direction. The flow is seen to vary subtly during the observation and it is believed to be attributed to the topography, the direction and velocity of the wind as well as tidal forces. A numerical experiments are conducted to explain the flow in the brackish lake using a three-dimensional simulation model. The flow simulation model favorably reproduces in the water levels and flow rate of each layer at narrow sections where most of the sectional flow rate is governed by tides. On the other hand around the mouth of bay, while the observed flow amplitudes are not well reproduced, there are good agreement in the temporal flow pattern.

INTRODUCTION

A prediction of the water quality of lakes can be made by simulations of the lake flow and primary production using an ecological model. The most important factor in evaluation of the water quality simulation model is the ability to reproduce the observed data. In reality, however, there are few observations on water quality or lake flow, available to analyze the ecological mechanism of lakes to a certain extent. Using an Acoustic Doppler Current Profiler (ADCP), which is usually used for ocean investigations and so forth, we have made flow observations of the semi-enclosed bay of a brackish lake that is regarded as having serious and difficult-to-analyze problems with water quality. In addition, we have developed a flow simulation model based on the multi-layer model, studied the flow mechanism and evaluated the model by verifying its ability to reproduce the observed data.

FLOW OBSERVATION

Observation location

Yonago Bay located in the southeastern part of Lake Nakaumi, a brackish lake in Shimane and Tottori Prefecture of Japan, is a typical semi-enclosed bay. Drainage from Yonago City, one of the biggest cities in the region, flows into the bay and red tides which are used so often to result from load stagnation due to the semi-enclosed bay are observed between autumn and spring every year. Yonago Bay is of the worst water quality (COD-75% value: 4.8 mg/l) (1) in Lake Nakaumi.

Flow observation by the ADCP

Flow observation was conducted with the ADCP which has recently replaced the current meter used in ocean investigations. An ultrasonic pulse with a constant frequency of 1200kHz is emitted underwater from four transducers and is reflected by fine suspended particles in the water, such as plankton. By measuring and analyzing the difference between the frequencies of the reflected and transmitted pulses, the ADCP can provide the direction of flow and velocity components in layers with the minimum interval of 0.25 m thick. It is not possible, however, to measure the difference either at the surface down to about 1.0 m, where the reflection time is extremely short, or deeper than 0.8D, where D is the total water depth, due to the random reflections from the lake bed. An ADCP was mounted on the research vessel which traveled at a speed of four knots. Location of the vessel was determined using the Global Positioning System (GPS).

Outline of observation

The observation was conducted once during a spring tide and once during a neap tide. Observation sites and items observed are shown in Figure 1. The velocity distributions across four sections A to D were measured, the sections being selected for their great topographical variations; and at the Nakaura gate (section D) where the bay is very narrow an electromagnetic current meter was used. Each observation period lasted for two tides (25.5 hours) with sample intervals of 1.5 hours during which time one observation cycle using the ADCP on sections A to C could be completed, for a total of 17 observations per section. Figure 2 shows the changes in water level during the observation. A drastic rise in water level is observed after 18:00 of November 23 during neap tide; the reason is unknown after eliminating the possibility of equipment trouble.

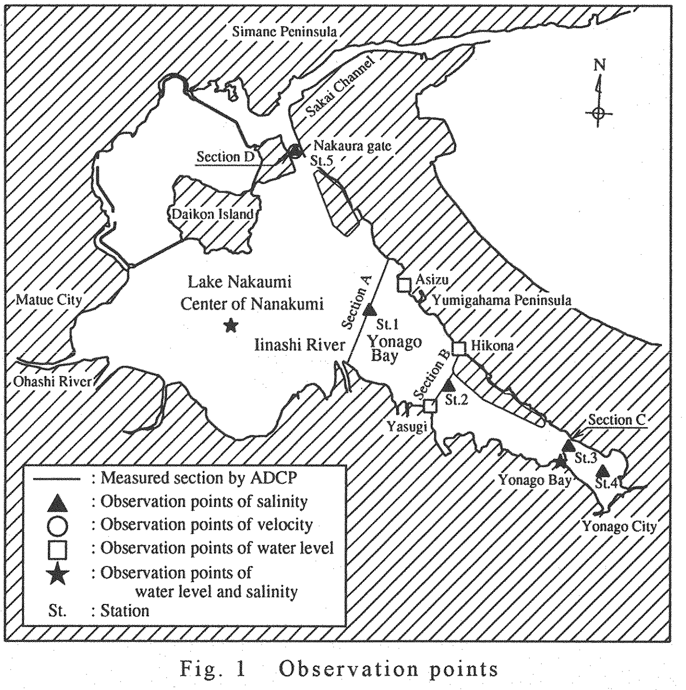

Fig. 1 Observation points

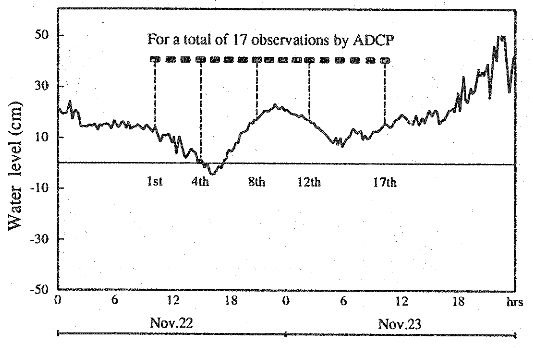

Fig. 2(a) Variation in water level during one neap tide cycle

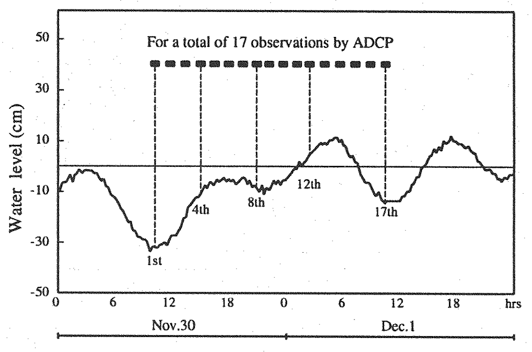

Fig. 2(b) Variation in water level during one spring tide cycle

OBSERVATION RESULTS

Figures 3 and 4 show the typical examples of surface current vectors and sectional distributions of current velocity in the 8th observation around section A during spring and neap tide. During spring tide, surface water flows into the bay at the mouth of the Iinashi River and exits along the Yumigahama Peninsula, i.e. surface water circulates clockwise. During neap tide, the complete opposite happens and surface water circulates counterclockwise. During spring tide, the sectional flow shows that the out-flow is mainly observed in the surface layer and the in-flow in the lower layer, but around the mouth of the Iinashi River the in-flow is observed in the surface layer. Around section B, there is a slight flow variation in cross-section but depth variations such as out-flow at the surface layer, in-flow at the middle layer and out-flow at the bottom layer become prominent. During every observation, though to a lesser extent in neap tide than in spring tide, each section is composed of flows with different direction both vertically and horizontally. The flow varies subtly from one observation to another, which is believed to be attributed to the topography, the direction and velocity of the wind as well as tidal forces. Figure 5 shows the vertical profiles of salinity at section A during spring and neap tide. Observation of the vertical salinity distribution was conducted at the same time as the ADCP observation. A salinocline is maintained during neap tide, while the vertical salinity gradient during spring tide is less distinct, and salinocline is disturbed by the flow. This trend in salinity distribution is very noticeable around all the three sections.

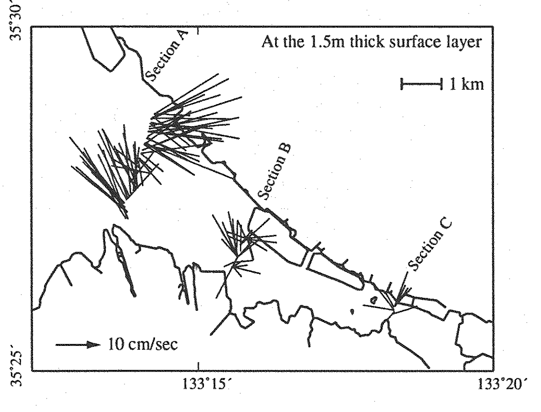

Fig. 3(a) Current vector distribution during a neap tide at the 8th observation

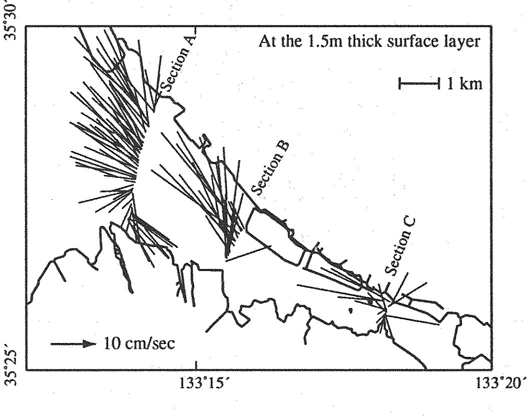

Fig. 3(b) Current vector distribution during a spring tide at the 8th observation

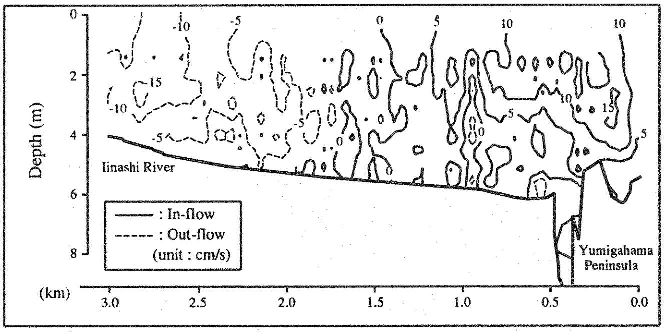

Fig. 4(a) Sectional current velocity distribution around section A during a neap tide at the 8th observation

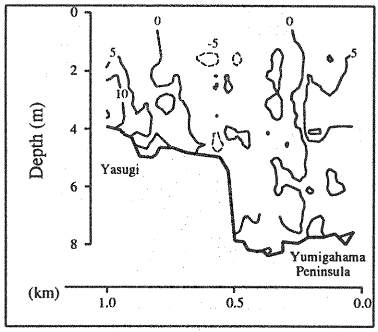

Fig. 4(b) Sectional current velocity distribution around section B during a neap tide at the 8th observation

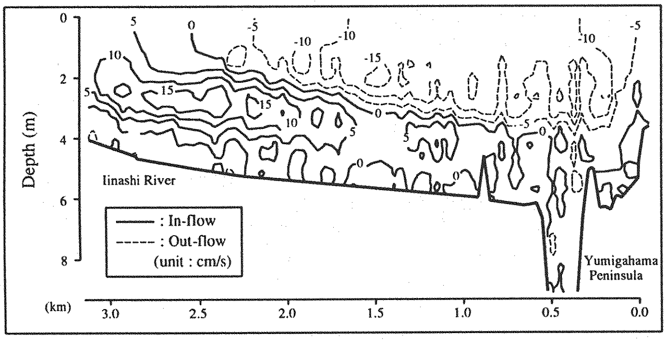

Fig. 4(c) Sectional current velocity distribution around section A during a spring tide at the 8th observation

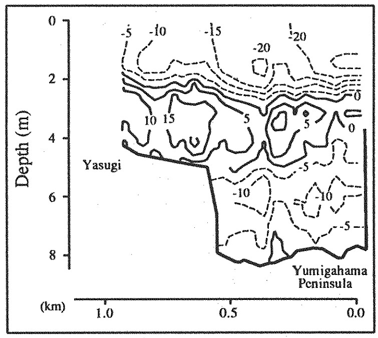

Fig. 4(d) Sectional current velocity distribution around section B during a spring tide at the 8th observation

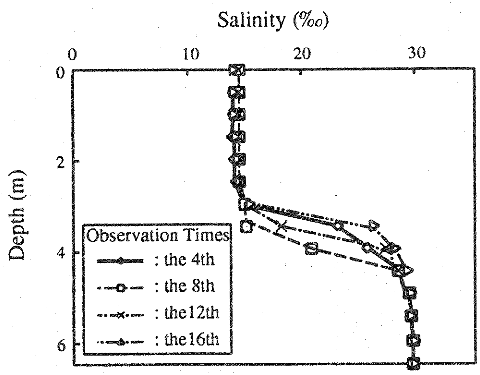

Fig. 5(a) Vertical profiles of salinity during a neap tide at the station 1

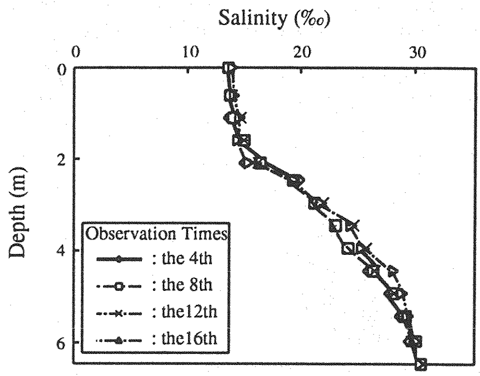

Fig. 5(b) Vertical profiles of salinity during a spring tide at the station 1

ANALYSIS OF THE FLOW RATE AND SALINITY FLUX

Calculation method of sectional flow rate and salinity flux

With the ADCP, horizontal flow velocities at different depths are assigned pixels (area elements). Assuming that the area of each pixel is dS' and the component of velocity of flow is Vn (m/s), the flow rate Q' (m^3/s) through the region S' for which the ADCP acquires data can be obtained by the following equation (2) is:

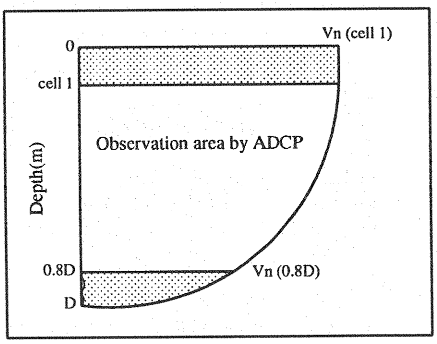

Fig. 6 Assumed current velocity distribution

$$Q' = \int_{B}^{A} \int_{cell1}^{0.8D} V_n \, d S' \qquad (1)$$

When the flow velocities at the surface and bottom area where measurement is impossible are assumed as shown in Fig. 6, total sectional flow rate Q is obtained by the following equation. The forth term of the Eq.2 indicates the flow rate through the region S'' close to the shore where measurement is impossible due to shallow water. Since this region S'' is much smaller in area than the region S', its flow rate can be expressed by multiplying the flow rate Q' by the area ratio (x=S''/S').

$$Q = Q' + \int_{B}^{A} \int_{0}^{cell1} V_n (cell1) \, d S + \int_{B}^{A} \int_{0.8D}^{D} V_n (0.8D) \, [1-(h-0.8D)/(D-0.8D)] \, d S + x Q' \qquad (2)$$

The salinity flux is calculated by the following method ; Salinity at depth intervals of 0.5 m by the salinity observation are méasured at the same time as the ADCP observation, and assigned to the pixels used in the ADCP analysis.

Analysis of the salinity flux

Figure 7 shows the sectional flow rate and salinity flux (= in-flow amount - out- flow amount) around section A. Though during neap tide, the salinity flux moves in roughly the same direction as the seawater flux, there is a difference in the timings of the two peak fluxes. This is because the seawater is exchanged with its salinocline intact, so different flows are present above and below the salinocline. During spring tide, the time change in the seawater and salinity flux corresponds well with each other because there is extensive mixing across the salinocline.

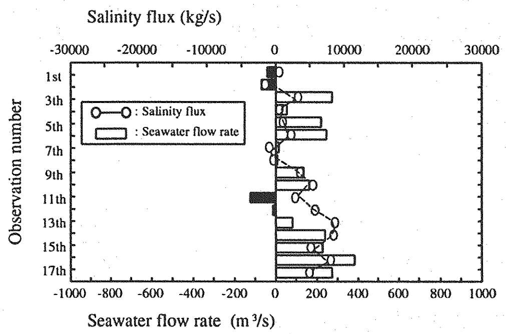

Fig. 7(a) Net seawater and salinity exchange during a neap tide around section A

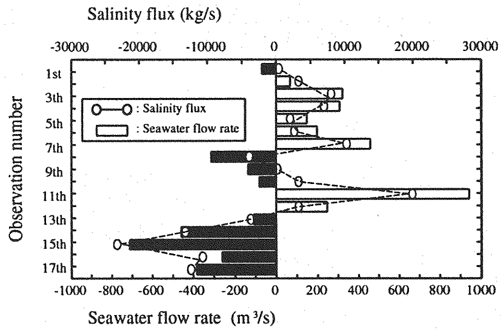

Fig. 7(b) Net seawater and salinity exchange during a spring tide around section A

FLOW SIMULATION MODEL

Using the observed data, a flow simulation model was developed and evaluated. Lake Nakaumi and Shinji constantly exchange seawater through the Sakai Channel with Miho Bay which faces the Japan Sea, maintaining stratification all through the year. The flow inside the lake is greatly affected by river discharges , tidal movement, wind blowing on the water surface and the topography of the bay and the lake bed. It is thus necessary to employ a three-dimensional non-static simulation model, taking the effects of density, tidal and drift currents into consideration in order to calculate the flow phenomena in Lake Nakaumi and Shinji.

Basic equations

A multi-level model was employed as the lake flow simulation model. The basic equations governing the flow consist of a continuous equation, equation of motion and thermal and salinity diffusion equations. Densities at the respective points of flow are calculated on the basis of water temperature and salinity (3).

Computation domain

The computation domain is shown in Fig. 8. The horizontal grid spacings, $\triangle x$ and $\triangle y$, are 333 m. The division of vertical layers is based on salinity observations in Lake Nakaumi and Shinji: 0 to 2 m, 2 to 4 m, 4 to 6 m and 6 m to the lake bed, where 2 m from the water surface corresponds with the upper limit of the salinocline in the lake, 6 m with the lower limit, and 4 m is the mid-point of the two.

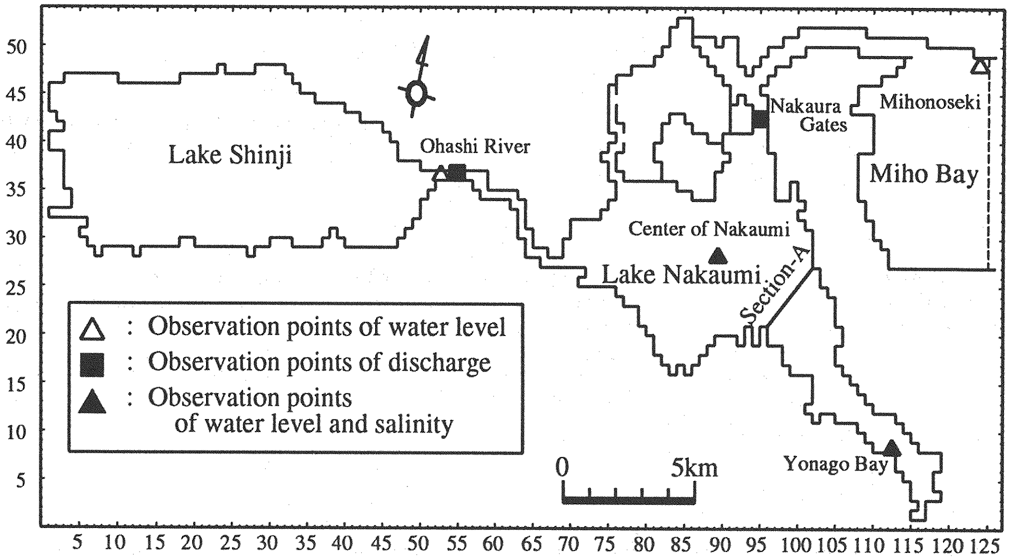

Fig. 8 Computation domain

VERIFICATION OF THE LAKE FLOW SIMULATION MODEL

Computation conditions for verification

Boundary conditions employed in flow computation are as follows. The discharges from the twenty-seven rivers are determined by multiplying the hourly observed discharge of the Hii River, the biggest of all, by the ratio of the basin area of each river to that of the Hii River. The observed temperature and salinity of incoming water from the Hii River are used for those for all the other rivers. The hourly observed tidal level of Miho Bay is used for the tidal level of the open sea boundary. The vertical profiles of temperature and salinity at the open sea boundary are obtained by averaging the observed results during the corresponding period. The directions and velocity of wind over each grid of lake is set based on the measurements at the nearest four observation points.

Parameter identification

Among the model parameters necessary for computation, the Coriolis parameter is set to $0.000084 s^{-1}$ and friction coefficient on the lake bed to 0.0026. The remaining parameters are identified by using computational reproducibility on the basis of hourly observation data of the water level in the lake, flow rate of the Ohashi River, vertical salinity distribution and the flow rate observation data of the Sakai Channel (2) and Yonago Bay obtained by the ADCP; as a result, the coefficient of horizontal viscosity = 40 m^2/s, the coefficient of friction at the lake surface = 0.0008, the coefficient of internal friction =0.0026, the coefficient of horizontal diffusion = 10 m^2/s, and the coefficient of vertical diffusion = 0.001 m^2/s.

Results of analysis

Analytical results of water level and flow rate, and salinity in the lake are shown in Figs. 9 to 12. Figures 9 and 10 indicate that the computed values for the water levels at the respective observation points and the flow rate through Ohashi River correspond well with the measured values. Figures 11 indicates that all the computed flow rates of each layer as well as the total sectional flow rate obtained at the Nakaura gate also agree favorably with the measured values. The flow through Ohashi River and Nakaura gate are mainly driven by tidal forces and in these regions the computed flow rates agree favorably with the measured values. Figure 12 shows the computed and observed flow rates of each layer around section A in Yonago Bay. In this area flow pattern of each layer is affected by the topography of the area and wind on the lake as well as tidal forces and the observed flow rates of respective layers vary from those at Nakaura gate in terms of the temporal flow pattern. Around section A, while the computed flow amplitudes of respective layers are overestimated and total sectional flow amplitude is underestimated when compared with the observed values, there are good agreements in the temporal flow patterns.

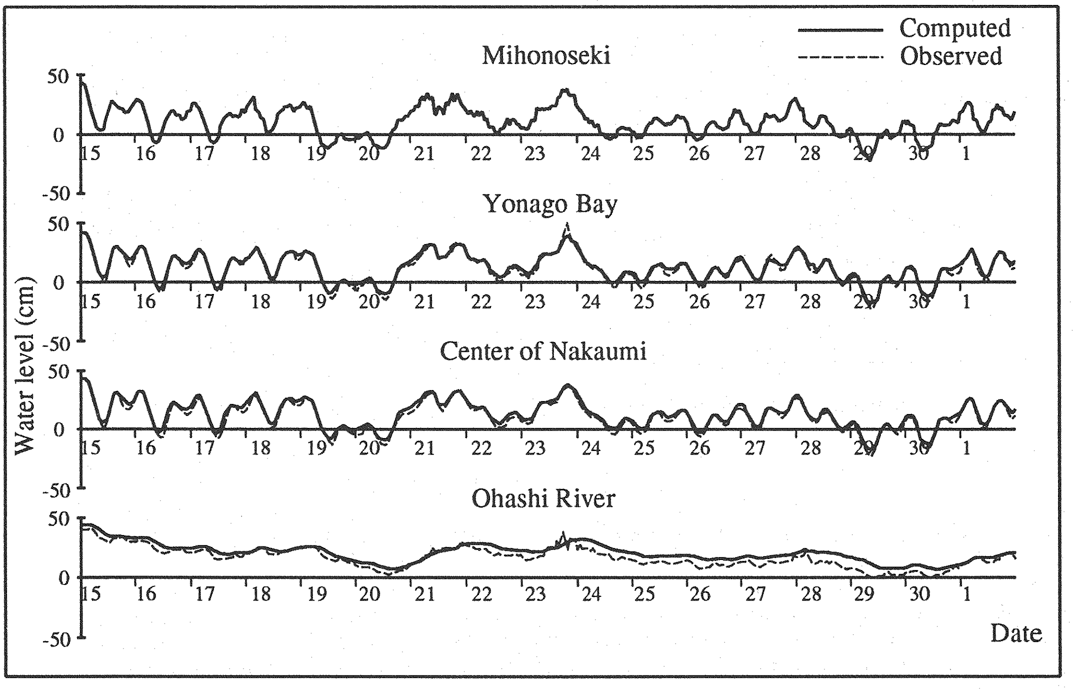

Fig. 9 Verification computation results of water level (Nov.15 - Dec.1,1993)

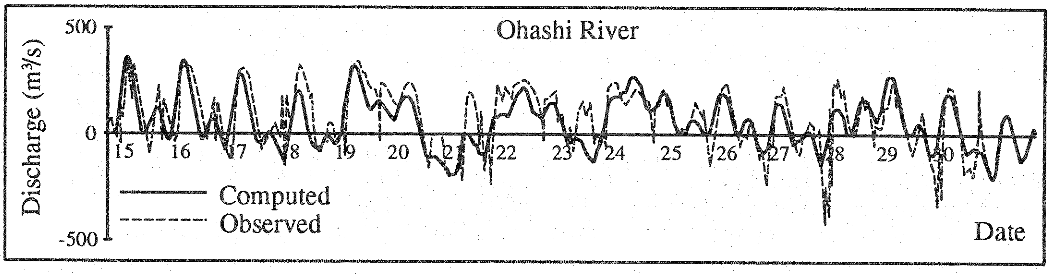

Fig.10 Verification computation results of discharge for Ohashi River (Nov.15 - Dec.1,1993)

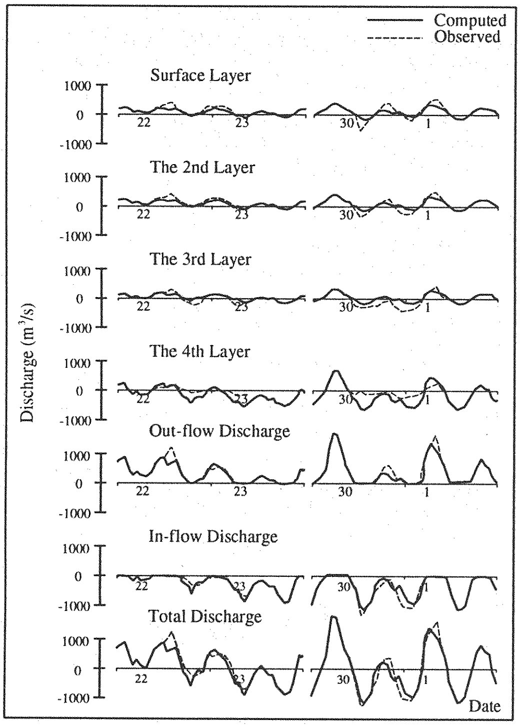

Fig.11 Verification computation results of flow rate for Nakaura gate (Nov.22-23 and Nov.30-Dec.1,1993)

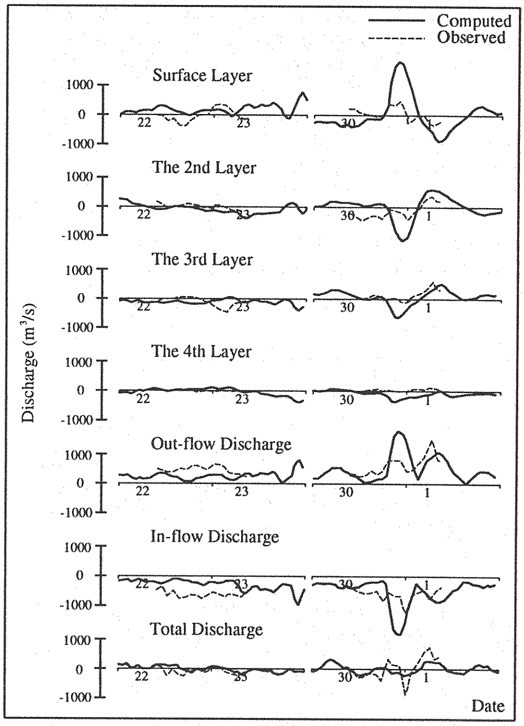

Fig.12 Verification computation results of flow rate for section A, Yonago Bay (Nov.22-23 and Nov.30-Dec.1,1993)

Figure 13 shows how the computed result of salinity of each layer at the center of Nakaumi and Yonago Bay corresponds with the observed value. The computed value for the bottom layer at the center of Nakaumi is constantly about 28‰, corresponding well with the observed value. However, for the surface layer, the computed value always remains somewhat higher than the measured value, and for the surface and second layers, the mixing and stratification that take place over time are not reflected in the computed values. The computed salinity for Yonago Bay are also higher than the observed ones; and the reproducibility of water mixing and stratification processes is still to be improved.

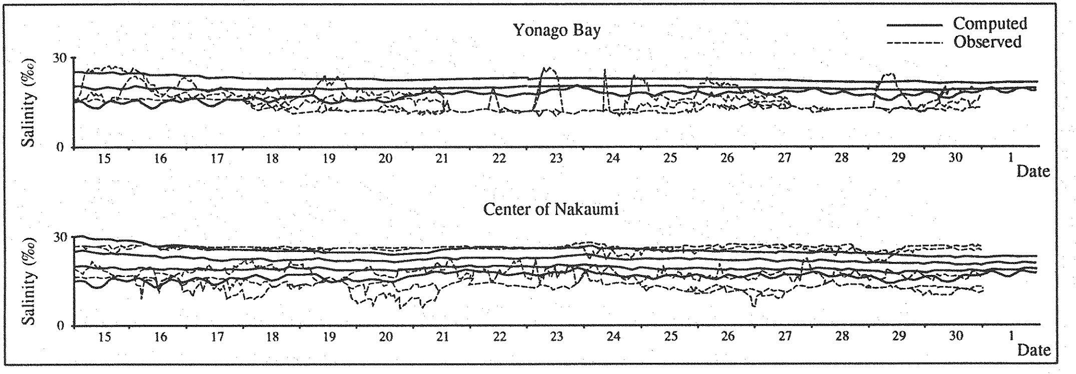

Fig.13 Verification computation results of salinity at the center of nakaumi and Yonago Bay (Nov.15 - Dec.1, 1993)

CONCLUSIONS

We have performed flow observations in the semi-enclosed bay of a brackish lake with ADCP. The results reveal for the first time some currents specific to this area, including a circulation around the mouth of bay. We believe that flow and salinity of each layer in Yonago Bay are greatly affected by the topography of the area and wind over the lake as well as tidal currents. Also, we have developed a flow simulation model to reproduce water flow peculiar to the area. It has been found that our flow simulation model favorably reproduces in the water levels and flow rate of each layer at narrow sections such as Ohashi River and Nakaura gate where most of the sectional flow rate is governed by tides. On the other hand, in wide areas such as section A of Yonago Bay where the sectional flow rate is governed by the topography of the area and wind over the lake as well as tides, while the observed flow amplitudes are not well reproduced, there are good agreements in the temporal flow pattern of each layer.

We plan to continue our observations to understand the circulatory flow generating mechanism at the mouth of Yonago Bay and the effects of circulatory flow upon seawater exchange in the bay. Eventually we intend to construct a flow simulation model that can explain the above in a satisfactory manner.

ACKNOWLEDGEMENTS

We would like to thank Dr. Setsuo Okuda (Professor, Okayama University of Science) and Mr. Tomotoshi Yoshimura and Yoichi Harada of Shin-Nihon Ocean Meteorological Co., Ltd. for their useful advice and cooperation in conducting the necessary observations and research.

REFERENCES

1. Shimane Prefecture : Report on observation results of water quality in public water area and ground water,1992.
2. Kansai Water Environment Res. Org. : Report on Investigation of Inflow and Outflow Rate around Sakai Channel, 1993.
3. Iwasa, Y : Lake Engineering, Sankaido, Japan, pp. 115-128, 1990.

(Received December 27, 1995; revised July 29, 1996)