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Characteristics of Salt Water Movement in Iwaki River Estuary, Japan

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Abstract: The present study aims to investigate the characteristics of the motion of salt water and to show the temporal fluctuation of the vertical salinity distribution in Lake Jusan located in the estuary of Iwaki River in Aomori Prefecture, Japan. The Lake Jusan is the best productive water area of the shellfish, corbicula, in Japan in 2013. Then, the lake is very important in Aomori Prefecture as corbicula's home. The change of the brackish environment influences the ecology of the corbicula shellfish, then, the shellfish harvest changes every year. Now, it is important to make clear the characteristics of the motion of salt water in the lake. In the present study, observations for the motion of the salt water going up to the lake and going down from the lake to the sea were carried out from June to September in 2015. The present study investigates the time change of the salinity distribution in a perpendicular direction and shows that the movement of the saltwater in the lake can be generated well by the theory given by Sasaki et al., 2009.

Key words: Estuary, river mouth, brackish water, saltwater, stratified flow, salt wedge, Iwaki River, Lake Jusan.

1. Introduction

The Iwaki River in Aomori Prefecture, Japan, flows through the Tsugaru Plains into Lake Jusan, and goes through the lake mouth into the Japan Sea (Fig. 1). Iwaki River is the first class river that is managed by the Ministry of Land, Infrastructure and Transport. The mouth of the Iwaki River, which becomes the mouth of the Lake Jusan, is locally referred to as Mitoguchi. Namely, the lake mouth is called Mitoguchi in local. In the past, there were many engineering works at the river mouth to make a new river channel from the lake to the sea. However, all those river channels newly developed were destroyed by high waves during rough seas caused by strong westerly winds in winter [1]. The lake overflowed, and the blockage of the water channel caused an extensive flood in the lower river basin. These floods caused considerable damage in the lower river basin of the Iwaki River and in all areas adjacent to Lake Jusan. There were two kinds of floods in Iwaki River. They were the floods due to the increased rainfall, and the floods due to the blockage of the water channel. Local inhabitants therefore petitioned the national government to implement flood control measures in the Iwaki River. The government established a construction office at Goshogawara town in the river basin, and the flood control measures by the nation were initiated in December 1918. When eight-year observations in the estuary for the geographical characteristics, and waves, and water currents passed, the construction of the Mitoguchi jetty to prevent the blockage of the river mouth started as a pier from land to sea in 1926. While initial efforts were focused on the construction of a pier on the northern side of the river mouth, in 1928 it was decided to construct jetties because the effectiveness of the pier as a jetty was excellent. Construction was initiated on the south jetty in 1930, and the entire Mitoguchi jetty construction project was completed 20 years later in 1946.

As a result, the river project provided environments of safe sailing of boat in the river channel, and of preventing blockage of the river mouth and of seawater entering the lake as shown by Sasaki and

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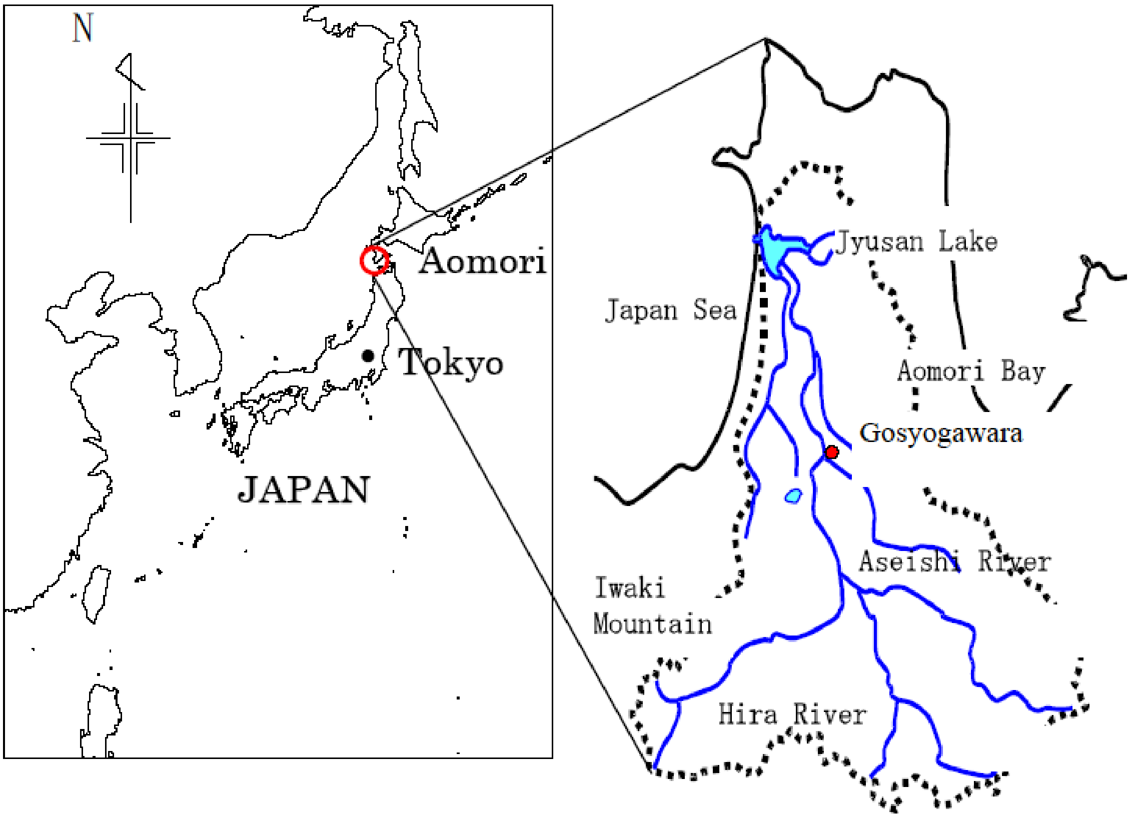

Fig. 1 Lake Jusan and Iwaki River.

Fig. 2 Observation station shown by a sign ▼ in 2015.

Takeuchi [1]. However, given the marked impact these changes have had on the water quality of the estuary system, we observed saltwater movement in the river mouth in this study. Lake Jusan is important lake in Aomori Prefecture as corbicula's production area. Because the corbicula grows up in the brackish lake, the motion of salt water to the lake causes the important effect for the growth of the corbicula.

Sasaki et al. [2] have already shown the movement of saltwater in the Lake Jusan and investigated horizontal distributions of the saltwater moving in the lake. They showed that the seawater goes up to the south lake through the lake center and reaches the south shore of the lake and that the seawater moves to the interior east of the lake through the shallow area near the east of the lake, and reaches the east end of the lake. And they also showed that the mixing of the freshwater into the seawater occurs considerably in the lake. Then, they investigated the time change of the salinity in the horizontal direction with the field observations in the study. Sasaki et al. [3, 4] showed the theory on the stratified flows of salt water in middle of the lake, and Sasaki et al. [5] showed that their theory can generate the stratified flows of salt water in the lake.

In the present study, the characteristics of the stratified flows of the salt water are investigated. Field observations were carried out for the movements of the salt water going up to the Lake Jusan and going down from the Lake Jusan to the sea from June to September in 2015. In the observations, water temperature, the flow direction, the flow velocity, and the salinity are measured. To supplement the field observation limited timewise and spatially, the saltwater movement was investigated by using the theory given by Sasaki et al. [4].

2. Field Observations for Salt Water Movement

Field observations were carried out for the motion of the salt water going up to the Lake Jusan and going down from the Lake Jusan to the sea during the period from June to September 2015. In the observations, water temperature, electric conductivity, the flow direction, the flow velocity, and the density of salinity were measured. The water qualities also were measured at a station shown in Fig. 2. The observation point was installed in the middle of the lake in 2014 [5], however, the observation point of 2015 is near the lake mouth than the observation point of 2014. Fig. 3 shows the salinometer and current meter used in the field observation. Fig. 4 shows the meters set up at the observation station shown in Fig. 2. As shown in Fig. 5, current meter was set up at the 57 cm height from the lake bottom. The salinometer was set up at the positions of four heights in 2015. Those heights were 30, 60, 90 and 120 cm from the lake bottom. The height of 30 cm was taken for two weeks from 14th

Fig. 3 Salinometer and current meter.

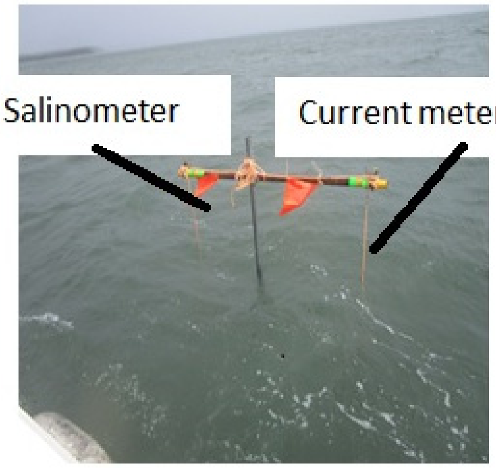

Fig. 4 Observations for salinity and flow velocity during the period from 14 July to 14 September 2015. The water depth is about 130 cm.

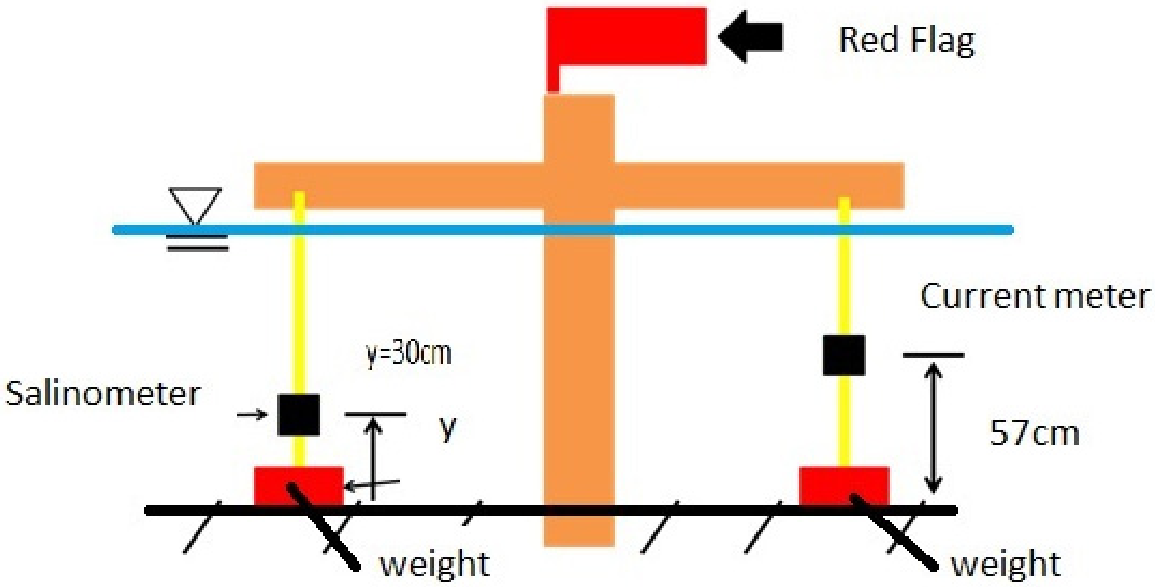

Fig. 5 Current meter was set up at the 57 cm height from the lake bottom. Salinometer was set up at the 30 cm height from 14 July to 31 July, and after that, it was taken at 60 cm height for 2 weeks from 1 August, and next, at the 90 cm height for 2 weeks from 16 August, and the last, at the 120 cm height for 2 weeks from 1 September. In this station, the water depth is about 130 cm.

July from 31st July, the 60 cm height was taken for two weeks from 1st August to 15th August, and the 90 cm height was taken from 16th August to 31st August, and, the height 120 cm was taken for the last two weeks from 1st September to 14th September.

3. Characteristics of Flow in Lake Jusan

The water level in Jusan Lake and the river discharge entered to the Jusan Lake have been observed by the local office of the Ministry of Land, Infrastructure and Transport. We can get the data on the water level and river discharge. Then, the velocity in the lake mouth can be calculated from the observation data given by the Japanese government local office. In the calculation, the mass continuity is used as shown in Eq. (1). Namely, the Lake Jusan is located in the river mouth, then, the equation of continuity can be shown as follows.

$$Q_1 - Q_2 = A_l \frac{\partial \eta}{\partial t} \qquad \therefore Q_2 = -A_l \frac{\partial \eta}{\partial t} + Q_1 \quad (1)$$

Where, Q_1 is the river discharge that enters from the river to the lake, Q_2 is the flow discharge in the entrance from the lake to the sea, A_l is the area of the lake, η is the water level of the lake, and t is time. In Eq. (1), the discharge Q_2 becomes positive as water goes down from the lake to the sea, and negative as water goes up to the lake from the sea. When the discharge Q_2 becomes negative, the sea water went up to the lake before the flow direction changes. The time of the stratified flows to the lake before the direction change near the bottom in the lake mouth is short. Therefore, the negative value of Q_2 means the discharge of the salt water entering to the lake from the sea, and the positive value of the discharge Q_2 means the discharge of the fresh water from the lake to the sea.

Fig. 6 shows the discharge in the lake mouth from 14 July to 31 July in 2015. As shown in the figure, the discharge Q_2 changes every day except during for few days from 25 July. The water level of the lake rose because there was a small-scale flood on 25 July due to the rainfall, so the backflow did not occur for three days from 25 July. The fluctuation of the discharge is caused by the vertical motion of the sea water level induced by the tide. The water levels of the river and the sea influence the lake water level. The water level of the river rises only when it rains and the river water increases, however, the water level of the sea rises and descends every day due to tidal wave. The water level of the lake becomes lower than the sea water level when the lake water level is rising after descending. At that time, the backflow is caused in the mouth of the Lake Jusan, and the sea water goes up to the lake. As mentioned above, the negative value of Q_2 means the backflow from the sea to the lake. Then, the backflow is caused every day if the river discharge is a little. As mentioned above, there is no backflow on 26 July. This is due to the rainfall on 25 July. Because the river discharge increases as shown in Fig. 6, the lake water level rises.

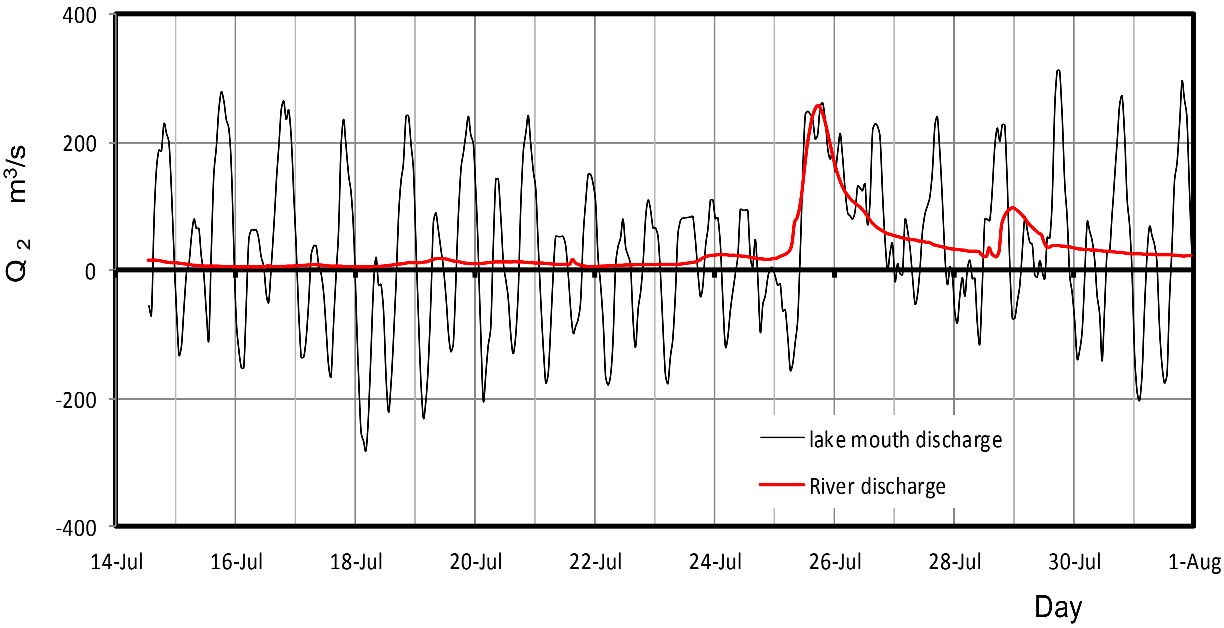

Fig. 6 Discharge in the mouth of Lake Jusan. The discharge Q_2 becomes positive as water goes down from the lake to the sea, and negative during the backflow.

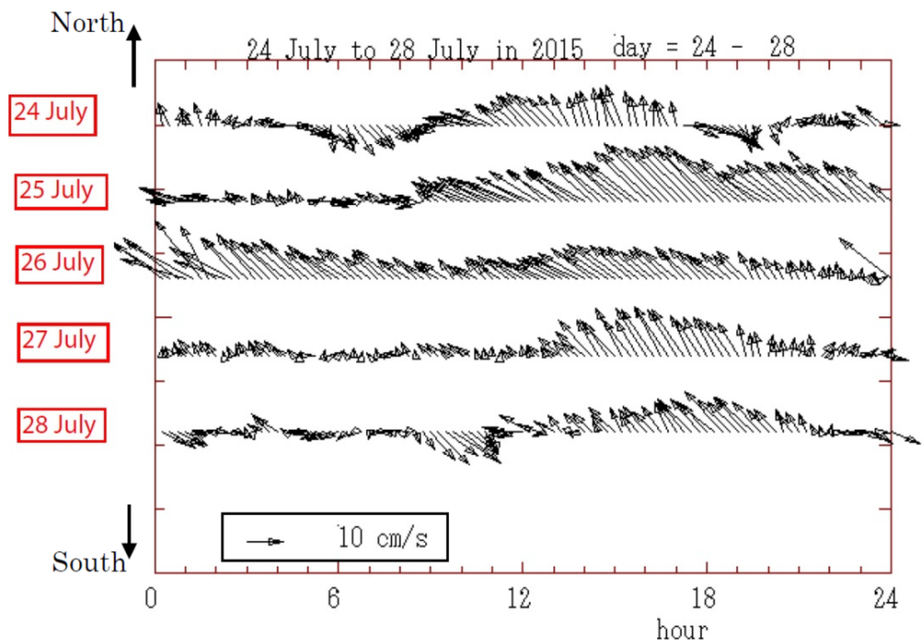

Fig. 7 An example of current observations in Lake Jusan from 24 July to 28 July in 2015.

Fig. 7 shows an example the results of field observations for the velocity and the direction of the current at the observation station near the lake mouth in the middle of the lake as shown in Fig. 2. The measurement of the velocity was made at the 57 cm height over the lake bottom as shown in Fig. 5. In Fig. 7, the northward velocity is showing the movement of the lake water that goes down through the lake mouth to the sea from the lake, on the other hand, the southward velocity is showing the backflow through the lake mouth from the sea into the lake. As shown in Fig. 7, there are some backflows around 6 in the morning and about 18 in the evening on 24 July, and about 10 in the morning on 28 July, however, there are seaward flows all day on 26 July. The seaward flows are due to the small flood caused by the rainfall in the Iwaki River basin. Comparing between Figs. 6 and 7, flows in the lake are following to the flows in the lake mouth. Then, we can conclude that the velocity in the lake is made and controlled by flows in the lake mouth.

4. Saltwater Movement in Lake Jusan

The saltwater movement in the lake is shown by the change of the salinity of the lake water. Sasaki et al. [3] have shown the theory about the movement of salt water in a river estuary, and Sasaki et al. [4] improved their theory, and have completed it. The theory given by Sasaki et al. [4] is as follows. Now, the mass per unit volume of the diffusion material is written by c. Then, the salinity is given by the diffusion material c. The diffusion material c is shown by the diffusion equation of Fick. On the seawater movement in the mouth of a river, we assume that the phenomenon is the same in the direction of the crossing. Then, the phenomenon of the seawater movement is shown by the next expression, Eq. (2).

$$\frac{\partial c}{\partial t}+u\frac{\partial (c)}{\partial x}=\frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial c}{\partial z}\right) \quad (2)$$

In Eq. (2), t is time, x is horizontal coordinate in direction of main flow, z is vertical coordinate, D_x and D_z are turbulent diffusion coefficients and u is velocity component of the flow in x directions. The coordinate x is taken from the river to the sea. The field of diffusion is divided into some layers along the depth for easiness now. The change in a perpendicular direction is assumed to be omissible small compared with the change of horizontal direction in each layer. Therefore, Eq. (2) can be written as the next Eq. (3) in the division water layer of k_{th}.

$$\frac{\partial c_k}{\partial t} + u_k \frac{\partial (c_k)}{\partial x} = \frac{\partial}{\partial x}\left(D_{xk} \frac{\partial c_k}{\partial x} \right) + q_k \quad (3)$$

where,

$$q_k = f_{zk} |u_k| \frac{\partial c_k}{\partial x} \quad (4)$$

$$D_{xk} = l_{xk} |u_k| \quad (5)$$

In Eqs. (3) and (4), q is an amount of the material movement by the mixture between layers. In Eq. (4), f_z is a coefficient for the mixture between layers. In Eq. (4), f_z is a coefficient for the mixture between layers and l_x is the mixing length. By taking some assumptions, Sasaki et al. [4] showed the theoretical solutions (6) and (8) of Eq. (3).

For the back flows from the sea to the lake,

$$c_k = \left(C_{3k} - C_{1k}\right)\{1 - \exp(-\alpha_{1k}\xi_k)\} + C_{1k} \quad u<0 \quad (6)$$

where,

$$\xi_k = 0 \qquad if \quad \xi_k < 0 \quad (7)$$

For the down-flows from the lake to the sea,

$$c_k = \left(C_{pk} - C_{1k}\right)\exp\{-\alpha_{2k}(\xi_k - \xi_{ok})\} + C_{1k} \quad u>0 \quad (8)$$

where,

$$c_k = C_{pk} \qquad at \quad \xi_{ok} = \xi_k (t = 0) \quad (9)$$

$$\xi_k = \beta_{1k} \int |u_k| dt / l_o + \beta_{2k} x_k / l_o + X_{o1k} / l_o \quad (10)$$

In the calculation of Eq. (8), when the value of $\xi_k - \xi_{ok}$ becomes negative, it is assumed $\xi_k - \xi_{ok} =$ 0 from Eq. (9). Namely,

$$\xi_k - \xi_{ok} = 0, \text{ if } \xi_k - \xi_{ok} < 0 \quad (11)$$

In above equations, ξ_k is a new variable defined as the equations (10), β_{1k} and β_{2k} are arbitrary constants that keep the type of the differential equation, X_{o1} is the position of the seawater front when $t = 0$, and l_o is a typical length of the field. In Eqs. (6) and (8), α_{1k} and α_{2k} are constants which are always positive. As above mentioned, the solution given as Eq. (6) is for the backflows. And the solution obtained as Eq. (8) is for the down-flows to the sea. In Eqs. (6) and (8), time becomes 0 at the commutation of the flow, and it starts respectively when the backflow and the down-flow begin, and constants C_{1k} and C_{3k} are the minimum value of the salinity and the maximum value of the salinity at any point x in the division water layer of k_{th}.

Fig. 8 shows an example of the comparisons between theory and observation for 2 weeks from 27 July 2015 in Lake Jusan. In the figure, the theory given by Eqs. (6) and (8) is shown by a black solid line. The calculation of the salinity is made at the 60 cm depth over the bottom near the center of the lake. In the theory, usually, the constant α_1 seems to be a range from 1 to 5, and the constant α_2 seems to be around 1. Those two constants are the important parameters that have relation with the saltwater movement. If they are not appropriate values, the theory is not suitable for the observations. As shown in the figure, the theory and the observations show a good agreement except on 7 August. A little disagreement has the cause in giving uncertain flow velocity obtained from Eq. (1). Then, it suggests that the theory generates well the salt water going up, the strength of salinity, and the continuance time of the backflow. As well as the salinity at the height of 60 cm, the comparison between the theory shown in Eqs. (6) and (8) and the observations also shows a good agreement for salinity at the height of 30, 90 and 120 cm over the lake bottom, although showing was omitted. As shown in Fig. 8, the salinity concentration in the lower water layer near the lake bottom reaches to the magnitude of the seawater. According to the observations, after the seawater is going up to the lake, water in upper layer becomes thin saltwater near the

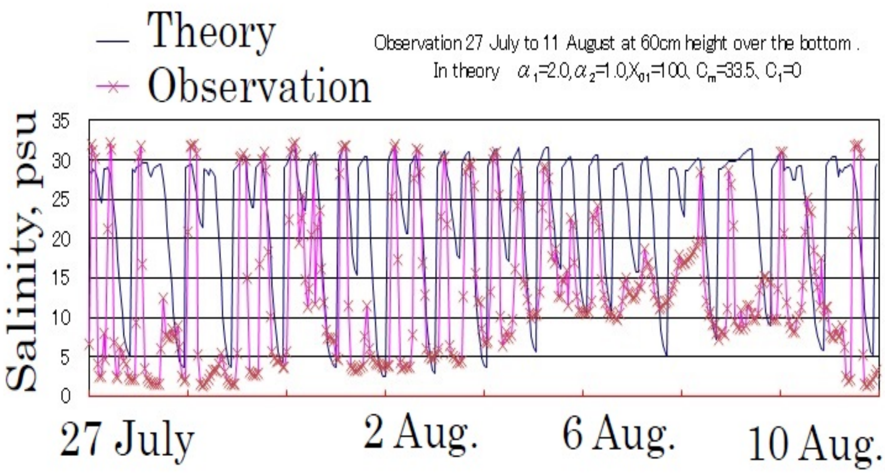

Fig. 8 Comparison between the theory given by solutions (6) and (8) and the observations shown by red line with *X* for salinity at a depth 60 cm from the lake bottom on 27 July-11 August, 2015. In the calculation, the constants $\alpha_1 = 2.5$, $\alpha_2 = 1.3$, $X_{o1} = 100$, $C_m = 33.5$ and $C_1 = 0$ are used.

freshwater due to the mixing between the freshwater and the seawater. It suggests that the salinity is changing between the freshwater and seawater within several days.

Figs. 9a-9c show the vertical distributions of salinity calculated by the theoretical solutions (6) and (8) for three months during July, August and September in 2015. In these figures, colors of light blue, yellow, blue, pink and red are used for the salinity concentration of 0-6, 6-12, 12-19, 19-26 and 26-32 psu, respectively. As shown in Fig. 7, because the lake water is moving always, light blue shows the fresh water flows, and red shows salt water flows. As shown in Figs. 9a-9c, the upper layer of the water depth near the water surface has the fresh water flows frequently in July and September, and even August in 2015. However,

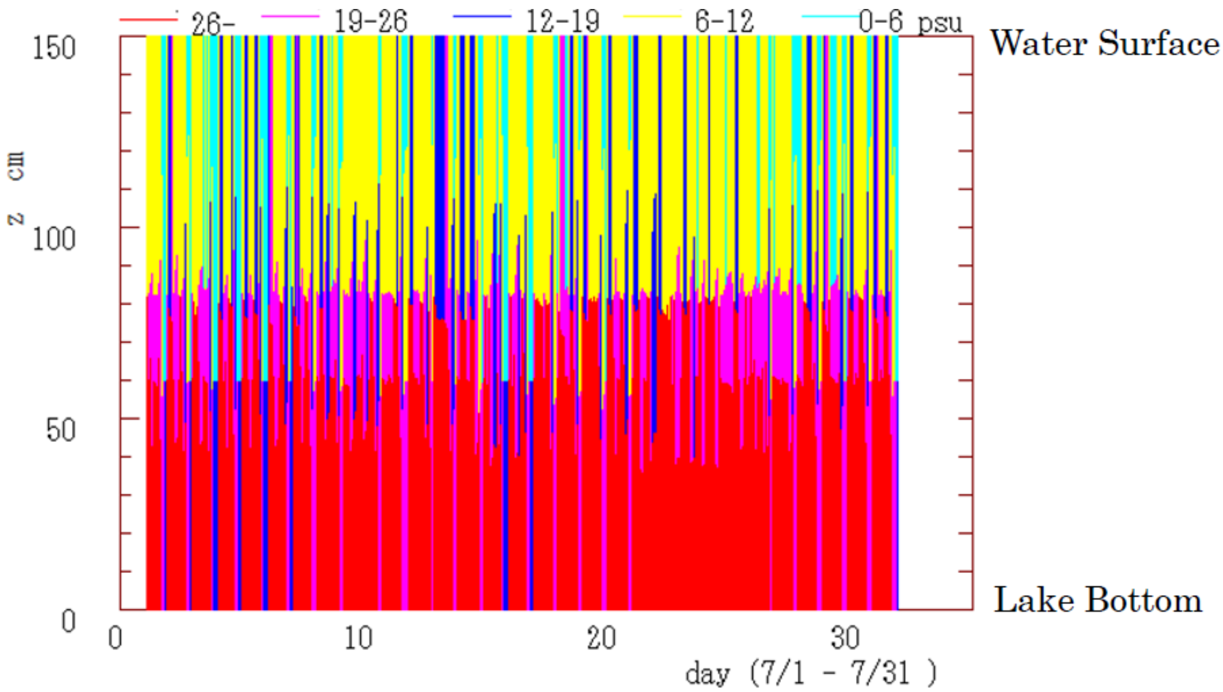

Fig. 9 (a) Vertical distribution of salinity given by solutions (6) and (8) at the center of the lake during July in 2015.

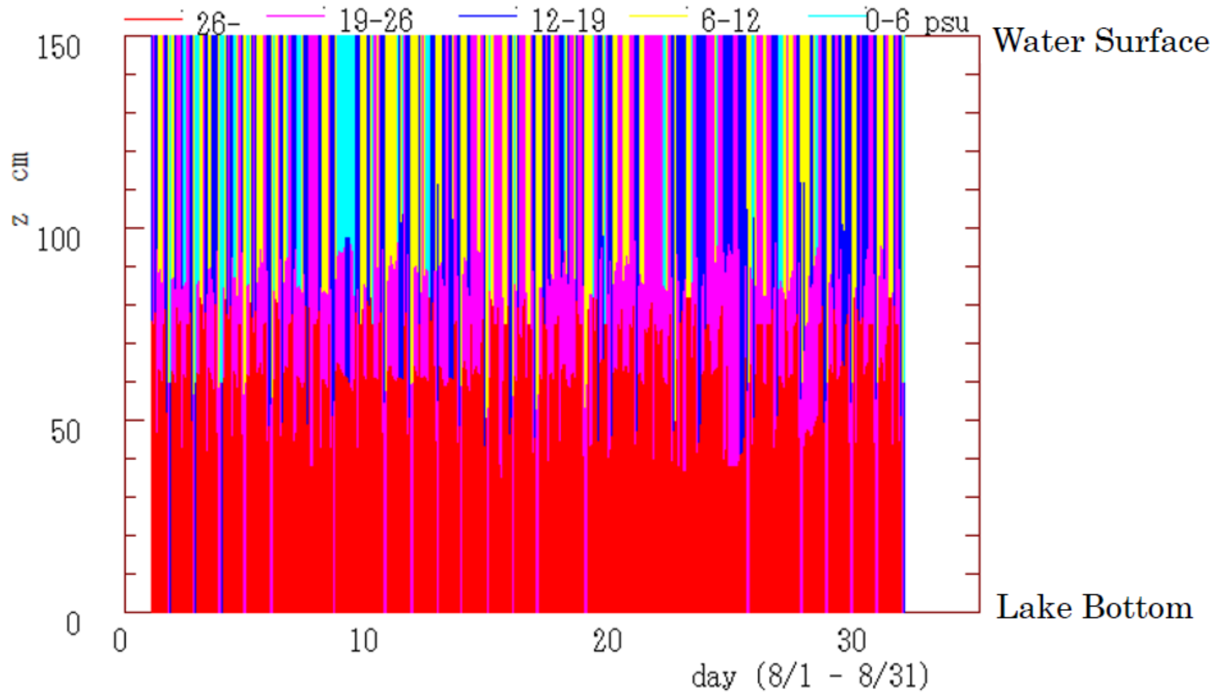

Fig. 9 (b) Vertical distribution of salinity given by solutions (6) and (8) at the center of the lake during August in 2015.

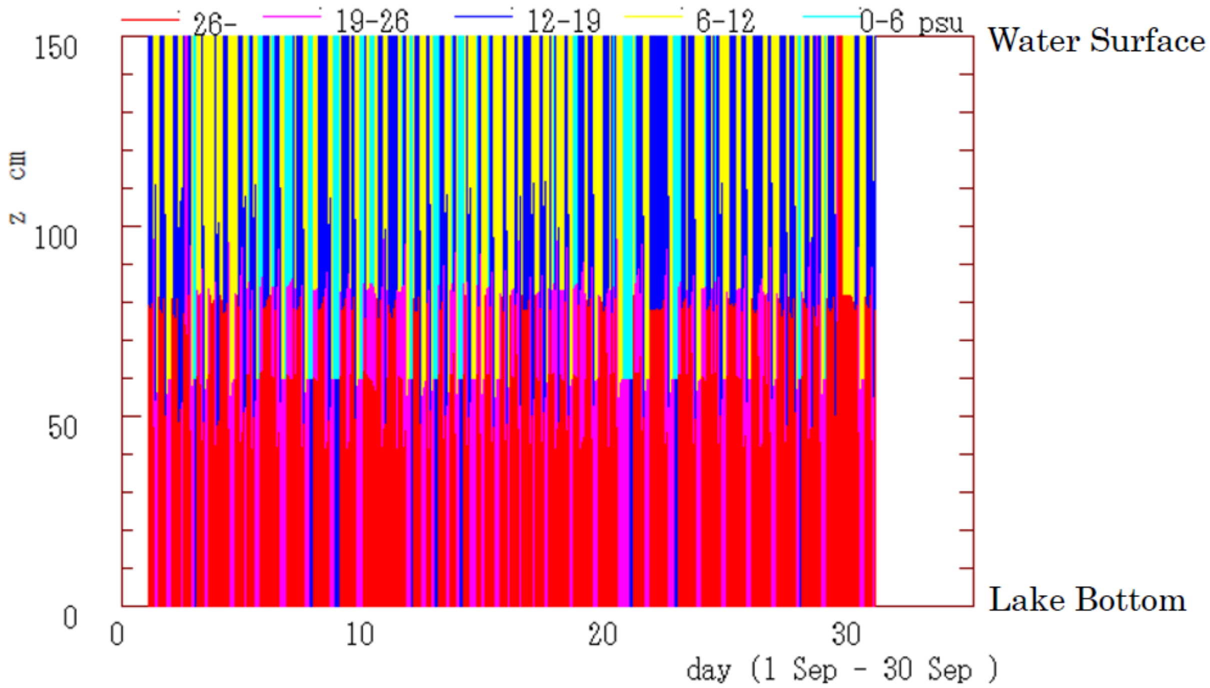

Fig. 9 (c) Vertical distribution of salinity given by solutions (6) and (8) at the center of the lake during September in 2015.

in August in 2015, the salt water remains in the lower layer of the water depth near the bottom of the lake for more than 25 days. This remaining of a long term of salt water is not good for corbicula's living environment. That is, they are waiting for salinity to thin moderately without breathing in strong salt water. They die if remaining of strong saltwater continues long. A large amount of corbicula were discovered to be dead in September 2015. This is because seawater remained in the lower layer of water near the bottom of the lake for 25 days or more in August 2015. In September 2015, fresh water flow occurred in the lower layer of water near the bottom of the lake just like the ordinary year within a week.

5. Conclusion

In the present study, the characteristics of the motion of salt water and the temporal fluctuation of salinity in Lake Jusan are investigated with the field observations made at the central of the lake from 14 July to August 2015 and the theory given by Sasaki et al. [4]. The present study shows as follows.

The comparison between the theory of Sasaki, Tanaka and Umeda and the filed observations shows a good agreement. In the theory, if the constants α_1, α_2, and X_{o1} are taken appropriate values, the theoretical solution given by Sasaki, Tanaka and Umeda can generate well the movement of seawater going up and down in Lake Jusan. The salinity concentration in the lower water layer near the lake bottom reaches to the magnitude of the seawater.

In August, 2015, the salt water remains in the lower layer of the water depth near the bottom of the lake for more than 25 days. Such a long remaining of seawater is not good for corbicula's living environment. A lot of corbicula were discovered to be dead in September 2015. By estimating the perpendicular distribution of salinity in the lake by the theory, the reason of corbicula's death was found as follows. The dead of a lot of corbicula is due to the long remains of the salt water in the lower layer of water near the bottom of the lake for 25 days or more in August 2015.

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