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Characteristics of Saltwater Intrusion in Lake Jusan

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Abstract*—The present study investigates the saltwater intrusion from January to December for five years from 2013 to 2017 in Lake Jusan. The ratio of the salt water into Lake Jusan from the sea reaches at the level of 30 percent in all month except March and April. The ratio of salt water decreases up to several percent in March and April. There is a small flood due to snowmelt from the mountain terrain in March and April, so the amount of saltwater decreases at early spring. The amount of the saltwater intrusion is the largest in July. The amount of the saltwater entering into the lake decreases in September. The decreases of the saltwater intrusion in September comes from a large amount of rainfall at typhoon season in Japan. The amount of the saltwater intrusion that is averaged for five years from 2013 to 2017 reaches to 50-80 Mm^3 each month except March and April. The saltwater decreases to 23Mm^3 in March, decreases further in April, and is 4Mm^3. The saltwater reaches to 80 Mm^3 in July. The saltwater intrusion in July, August and September, 2017 occurs almost every day, however, the high density saltwater near the lake bottom is swept out almost every day. The high density saltwater doesn't stay on the bottom of the lake for a long term in 2017. The salinity changes in the middle and upper water layers in the mouth of Lake Jusan. The salinity in the upper water layer thins.

***Index Terms*— salt water intrusion, estuary, brackish water, river mouth, diffusion material, mixture flow, stratified flow, salt water wedge.**

I. INTRODUCTION

The present study takes the Lake Jusan as a field study area. The lake is brackish water and it is one of the big production of corbicula japonica, black sea shell in Japan. The Lake Jusan is located in the mouth of the Iwaki River in Aomori Prefecture, Japan. The Iwaki River flows into Lake Jusan after passing the Tsugaru Plains, and empties through the lake into the Japan Sea (Fig. 1). Iwaki River is a class 1 river managed by the Ministry of Land, Infrastructure and Transport. There is a waterway in the mouth of the Iwaki River, which is formed by Lake Jusan. The waterway is locally called Mitoguchi in this district. According to Sasaki and Takeuchi (2003) [1], in the past, there were many engineering works at the river mouth to make a new waterway, a new Mitoguchi, from the lake to sea. However, all waterways newly developed were destroyed during rough seas caused by strong westerly winds in winter. The river mouth had been blockaded four to five times a year as well as extensive flooding of the area as the lake overflowed (Sasaki and Takeuchi (2003) [1]).

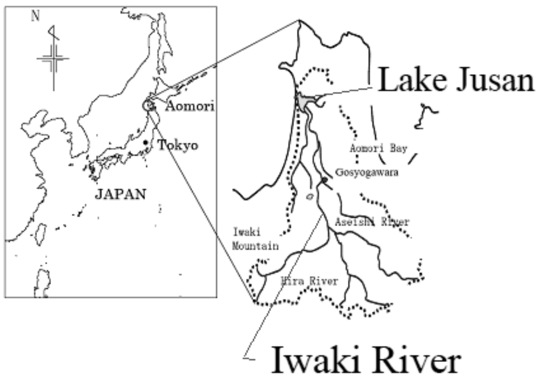

Fig. 1. Iwaki River and Lake Jusan.

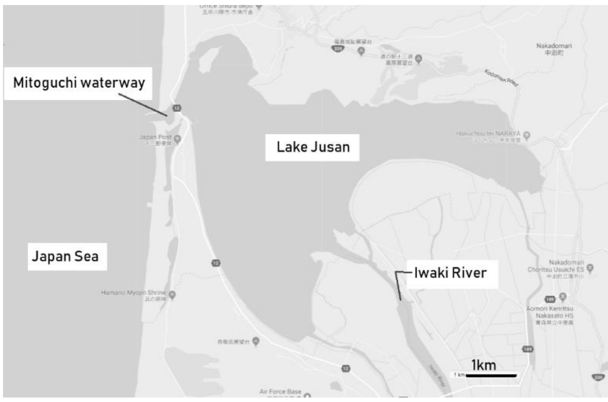

Fig. 2. Lake Jusan

These floods caused considerable damage to the lower river basin of the Iwaki River, and the areas adjacent to Lake Jusan. In the Iwaki River, this kind of flood damage can generally be classified as two types of natural disaster. One is flooding due to increased rainfall, and the other is flooding due to blockage of the river mouth. Local inhabitants therefore petitioned the national government to implement flood control measures in the Iwaki River. The government established a construction office in Goshogawara, and the flood control measures by the nation were initiated in December 1918. The construction of a new Mitoguchi jetty for preventing blockage of the waterway was started as a pier from land to sea in 1926 after eight-year study about the geographical characteristics, waves and current in the estuary had been completed. 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 instead of the pier that had given the effectiveness as a jetty. The construction was initiated on the south pier in 1930, and the entire Mitoguchi pier construction project was completed 16 years later in 1946. As a result, the new Mitoguchi jetties provided environments of safe sailing of boat in the waterway, and of preventing blockage of the river mouth, and the regular intrusion of seawater into the lake. However, these changes have had the marked impact on the water quality of the estuary system. Lake Jusan is important lake in Aomori Prefecture as corbicula's production area. Because the corbicula grows up in the brackish lake, the intrusion of salt water to the lake causes the important effect for the growth of the corbicula. The Lake Jusan was the first position in the production of corbicula in Japan in 2011.

However, the corbicula production in the Lake Jusan is under the influence of the variation of water environment which is changed by the abnormal water temperature rise, a large amount of river water flowed into the lake, and a lot of saltwater intruded to the lake. Now, it is very important to investigate the brackish water environment affected by the saltwater intrusion. Sasaki, Tanaka and Umeda (2012) [2] showed the saltwater intrusion into the Lake Jusan from 2003 to 2007. The present study aims to investigate the saltwater intrusion from January to December in 2013 to 2017. Sasaki, Tanaka and Umeda (2017) [3] showed the perpendicular distribution of salinity in the Lake Jusan by using their theory. The present study investigates the vertical distribution of the seawater intruded in the mouth of Lake Jusan by using the theory given by Sasaki, Tanaka and Umeda (2017) [3].

II. INFLOW WATER INTO LAKE

The Lake Jusan is taken as the field study area as mentioned above. The present study consists of the investigations for the amount of saltwater run-up into the lake, and for the vertical structure of the saltwater intruded in the mouth of the lake. First, the amount of saltwater into the lake from the sea is calculated. The calculation uses the mass conservation law in the Lake Jusan. There is one big river, Iwaki River flowing into the lake. There are some small rivers connecting to the lake. They are far smaller compared with Iwaki River. Then, only Iwaki River is taken as river in the mass conservation law in the lake. The discharge of the waterway, Mitoguchi which connects the sea and the lake, is also taken in the mass conservation. The discharge of the waterway gives the amount of the saltwater intrusion into the lake. Then, by calculating, the present study shows the characteristic of the saltwater intrusion each month from January to December in 2013 to 2017. Sasaki, Tanaka and Umeda (2017)[3] have shown the vertical salinity profile of the saltwater running up into the Lake Jusan. According to their theory, we can predict the saltwater intrusion near the mouth of the lake.

III. CHARACTERISTICS OF SALTWATER INTRUSION

There are two inflows in the lake as shown in Fig. 2. One is a fresh water from Iwaki River, and other one is seawater from the Mitoguchi waterway. The water level of the lake rises by the two inflows. Then, the mass conservation in the lake can be given as follows.

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

Where, Q_1 is the river discharge which enters from the river to the lake, Q_2 is the discharge of the Mitoguchi waterway from the lake to the sea, A_l is the area of the lake surface, η is the water level of the lake, and t is time. In (1), the discharge Q_2 becomes positive as water goes down from the lake to the sea, and negative during the backflow from the sea to the lake. When the discharge Q_2 becomes negative, the sea water went up to the lake before the flow direction changes. However, the time of the stratified flows near the bottom in the lake mouth is short, then basically, the positive value of the discharge Q_2 means the discharge of the fresh water from the lake to the sea, and the negative value of Q_2 means the discharge of the salt water entering from the sea to the lake. The water level in the lake and the river discharge have been observed by the local office of the Ministry of Land, Infrastructure and Transport. One can obtain the data on the water level and river discharge. Then, the discharge Q_2 in the Mitoguchi waterway can be calculated from the two observation data given by the Japanese government local office. From (1), the discharge Q_2 is given as follows.

$$Q_2 = -A_l \frac{\partial \eta}{\partial t} + Q_1 \qquad (2)$$

Fig. 3 shows the amount ratio of the fresh water and the salt water that enters to Lake Jusan per month. The ratio is averaged for five years from 2013 to 2017. As shown in Figure 3, the salt water reaches to 28 and 26 % in January and February, however, the ratio of salt water decreases up to several percent in March and April. There is much fresh water in March and April. The fresh water in April reaches to 99 %. There is a small flood due to snow melt water from the mountain terrain in March and April, so the amount of fresh water in Iwaki River becomes large at early spring. After that, the ratio of saltwater going up to the lake increases from spring to summer, and it reaches to 39 % in June, 39% in July, 21 % in August. However, the amount of the saltwater that flows to the lake decreases in September, and it increases up to 24 % in October. The decreases of the saltwater intrusion in September comes from a large amount of rainfall at typhoon season in Japan. The amount of the saltwater untrusion larsts 20 percent level in November and December. The ratio of the saltwater intrusion reches to 25 and 21% in November and

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December.

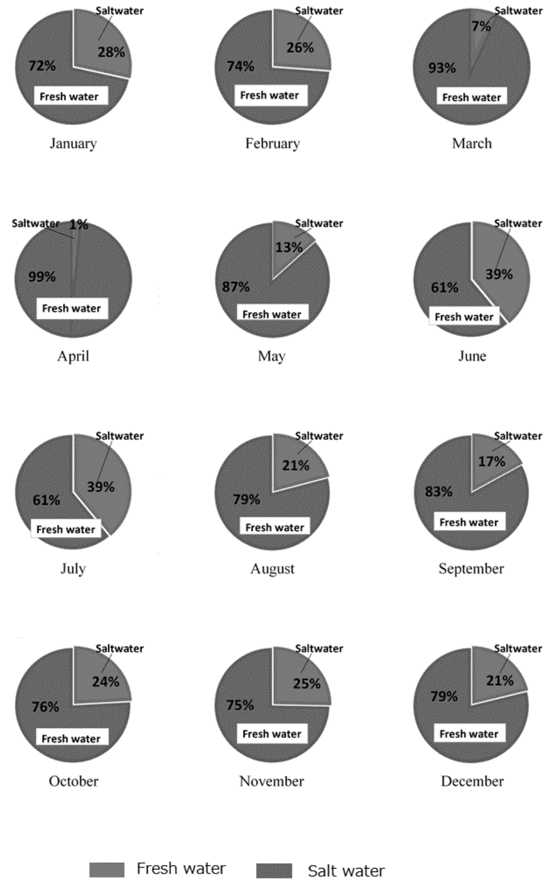

Fig.3. Ratio of amount of fresh water inflow and amount of salt water inflow

Fig. 4 shows the saltwater inflow and the freshwater inflow that enter into the Lake Jusan per month in each year from 2013 to 2017. Fig. 4(a) shows that the ratio of the saltwater inflow that enters into the lake increased more than that of the ordinary years like 9% in April in 2016, and 59% in June, 67% in July and 54% in August in 2015, and 59% in June in 2016 consequently. A little snowmelt amount comes from a few snowfall in winter.As shown in Fig. 4(b), the fresh water from the Iwaki River is a little in April in 2016 compared with the one of the ordinary year. However, in general, there is much fresh water from the river in April. The ratio of the amount of the freshwater in April is higher than that in other month. Due to the snowmelt from the mountain terrain, the amount of fresh water from Iwaki River is a large in March and April. The flood of snowmelt in early spring influences the amount of the saltwater inflow into the lake in May and June. The fresh water in April in 2016, May and June in 2015 was a little because the amount of snowmelt water was a little. Fig. 5 shows the amount of saltwater intrusion per month. In the figure, the amount is averaged for five years from 2013 to 2017. As shown in the figure, the amount of the saltwater intrusion is about 50Mm^3 in January and February, however, it decreases to 23Mm^3 in March, decreases further in April, and is 4Mm^3. And, it increases to 30Mm^3 in May, becomes 57Mm^3 in June, increases to 80Mm^3 in July, and is the maximum. It increases to about 60Mm^3 in October though it decreases to 60Mm^3 in August, and decreases to 40Mm^3 in September. and, it is about 60Mm^3 and 58Mm^3 in November and December.

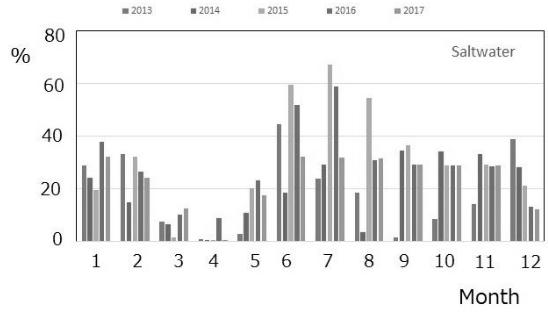

Fig.4 (a). Ratio of saltwater inflow

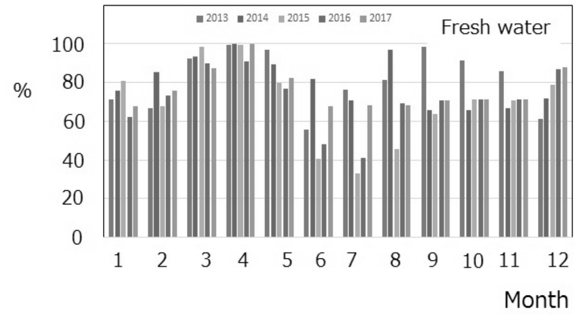

Fig.4 (b). Ratio of fresh water inflow

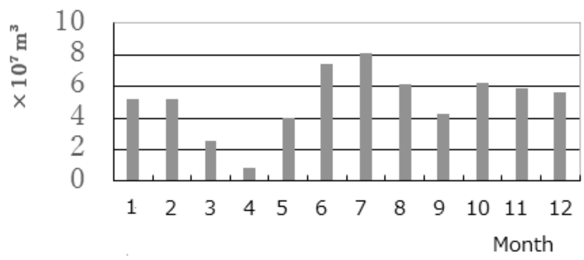

Fig. 5. Amount of salt water inflow averaged for five years from 2013 to 2017

IV. PERPENDICULAR DISTRIBUTION OF SALINITY IN LAKE MOUTH

Sasaki, Tanaka and Umeda (2017) [3] have shown the vertical salinity distribution of saltwater in the mouth of the Lake Jusan. Now, in the divided horizontal water layer of k-th, we take C_{1k} as the minimum value of the salinity and C_{3k} as the maximum value of the salinity. According to them, the salinity c_k in the k-th horizontal water layer can be given by the analytical solutions as follows.

For backflow from the sea to the lake

$$c_k = (C_{3k} - C_{1k})[1-\exp\{-\alpha_1(\xi_k + \xi_{ok})\}] + C_{1k} \qquad u<0 \tag{3}$$

Where

$$\xi_k = \beta_{1k}\int_0^t |u_k|\,dt / l_o + \beta_{2k} x_k / l_o + X_{o1bk} / l_o , \tag{4}$$

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$$\xi_{ok} = -\frac{\ln(\frac{C_{3k}-C_{ek}}{C_{3k}-C_{1k}})}{\alpha_{1k}} \qquad (5)$$

For seaward flow from the lake to the sea

$$c_k = \left(C_{pk} - C_{1k}\right)\exp(-\alpha_2 \xi_k) + C_{1k} \qquad u>0 \qquad (6)$$

Where

$$\xi_k = \beta_{1k}\int_0^t |u_k|\, dt / l_o + \beta_{2k} x_k / l_o, \qquad (7)$$

Where C_{ek} is the salinity at the moment when the backflow begins from the sea to the lake, and C_{pk} is the salinity at the moment when the seaward flow begins from the lake to the sea. The mixture coefficients between the freshwater and the saltwater α_1 and α_2, and the minimum and maximum values of the salinity in the diffusion field C_{1k} and C_{3k}, and the distance related to the saltwater intrusion X_{o1bk} at the depth z=30, 60, 90 and 120 cm over the lake bottom can be determined as follows.

At z=30 cm

$$\left.\begin{array}{l} \alpha_1 = 3.5 \\ \alpha_2 = 0.5 \\ C_{1k} = 0 \\ C_{3k} = 33.5 \\ X_{01bk} = 0 \end{array}\right\} \qquad (20)$$

At z=60cm

$$\left.\begin{array}{l} \alpha_1 = 2.0 \\ \alpha_2 = 0.5 \\ C_{1k} = 0 \\ C_{3k} = 33.5 \\ X_{01bk} = 0 \end{array}\right\} \qquad (21)$$

At z=90cm

$$\left.\begin{array}{l} \alpha_1 = 1.5 \\ \alpha_2 = 0.5 \\ C_{1k} = 0 \\ C_{3k} = 33.5 \\ X_{01bk} = 0 \end{array}\right\} \qquad (22)$$

At z=120cm

$$\left.\begin{array}{l} \alpha_1 = 0.3 \\ \alpha_2 = 0.5 \\ C_{1k} = 0 \\ C_{3k} = 33.5 \\ X_{01bk} = 0 \end{array}\right\} \qquad (5) \qquad (23)$$

Figs. 6, 7 and 8 show the vertical profiles of the saltwater that is entering into the lake in July, August and September in 2016. Fig. 6 shows that the saltwater intrusion occurs almost every day in July, and that, however, the salt water with high salinity concentration near the lake bottom is swept out almost every day. The high density salt water doesn't stay on the bottom of the lake for a long term in July, 2016.

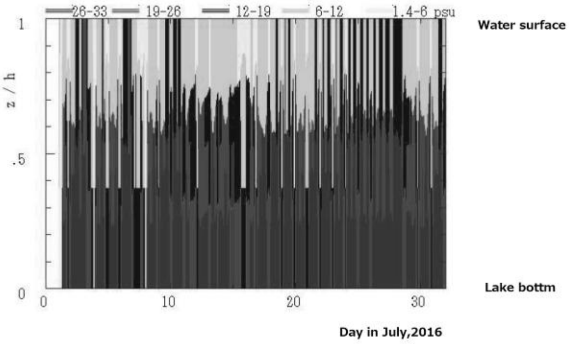

Fig. 6. Vertical distribution of Salt water intrusion in July, 2016

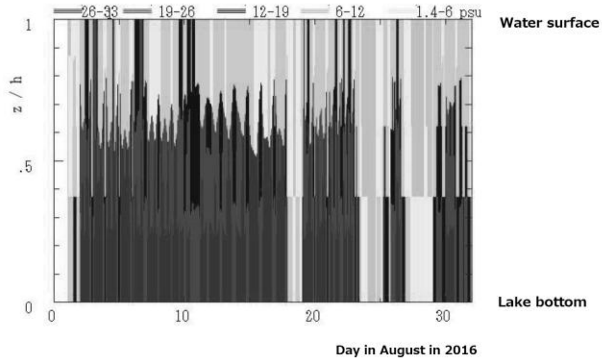

Fig. 7. Saltwater intrusion in August, 2016.

Fig. 7 is showing the prediction of the saltwater intrusion in August, 2016..As shown in the figure, the saltwater movement is the same as well as July, namely, the saltwater intrusion occurs almost every day in August, however, the saltwater with high salinity concentration on the lake bottom is swept out almost every day, therefore, the saltwater of high density doesn't stay near the lake bed for a long term in August, 2016. Especially, no saltwater intrusion occurs on 19, 23, 24, 27 and 28 August, 2016.

Fig. 8 shows the prediction of the saltwater intrusion in September, 2016. As shown in the figure, the movement of salt water is a little different in September, namely, the saltwater intrusion also occurs almost every day in September, however, the saltwater with high salinity concentration on the lake bottom is swept out almost every day, therefore, the saltwater of high density doesn't stay near the lake bed for a long term in September, 2016, too. The saltwater intrusion doesn't occurs on 11 and 12 September,

2016. And, the figure shows that the salt water of a low density runs up in the first half of September, however, the salt water of a high density runs up in the latter half of September, 2016. Figures 6, 7 and 8 are showing that salinity changes even in the middle and upper water layers.

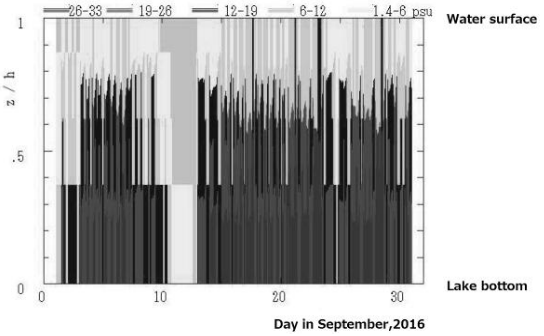

Fig. 8. Salt water intrusion in September, 2016.

V. DISCUSSION

The present study has investigated the saltwater intrusion in the mouth of the Lake Jusan, and made clear the vertical distribution of the salinity. The ratio of the salt water that enters the Lake Jusan reaches to 30 percent at all month except March and April. The ratio of salt water decreases up to several percent in March and April. There is much fresh water in April. The fresh water in April reaches to 99 %. There is a small flood due to snowmelt from the mountain terrain in March and April, so the amount of fresh water in Iwaki River becomes large at early spring. After that, the ratio of saltwater going up to the lake increases from spring to summer. The amount of the saltwater intrusion is the largest in July. The amount of the saltwater that flows to the lake decreases in September. The decreases of the saltwater intrusion in September comes from a large amount of rainfall at typhoon season in Japan. The amount of the saltwater intrusion that is averaged for five years from 2013 to 2017 reaches to 50-80 Mm^3 each month except March and April. The saltwater decreases to 23Mm^3 in March, decreases further in April, and is 4Mm^3. The saltwater reaches to 80 Mm^3 in July. The saltwater intrusion in July, August and September, 2016 occurs almost every day, however, the high density saltwater near the lake bottom is swept out almost every day. The high density saltwater doesn't stay on the bottom of the lake for a long term in 2016. The salinity changes in the middle and upper water layers in the mouth of the Lake Jusan. The method of the present study can be applied to the saltwater intrusion in other estuary. We think that it is very useful.

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