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Impact of Permeable Structures on Salinity Intrusion in the Abashiri River

IMPACT OF PERMEABLE STRUCTURES ON SALINITY INTRUSION IN THE ABASHIRI RIVER

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ABSTRACT

Hokkaido's Lake Abashiri is a fertile fishing ground, but its anoxic brine layer has demonstrated a rising tendency in recent years, thus increasing the risk of fishery damage. To combat this, a variety of measures have been taken to control salinity intrusion. In this study, the salinity intrusion control effect of permeable structures used to catch salmon was evaluated by numerical calculation. The study produced the following findings : 1) The validity of the one-dimensional, two-layer flow model constructed in this study was confirmed over a period of 20 days including high and low tides. 2) The numerical calculation results revealed that the salinity intrusion control effect increased when permeable structures had finer meshes. The controlling effect of positioning structures upstream was also greater than that of increasing their number.

Key Words : *salinity intrusion, brine, controlling effect, calculation, Abashiri, Hokkaido*

1. INTRODUCTION

A diverse ecosystem is formed in the tidal compartments of rivers, such as the Abashiri River in eastern Hokkaido, which has Lake Abashiri situated approximately 7 km from its mouth. **Figure 1** shows a schematic map of the surrounding area. Due to salinity intrusion into Lake Abashiri, it is a brackish-water lake with a brine layer at the bottom and a freshwater layer at the top. Its freshwater layer is a fertile fishing ground for freshwater clams, surf smelt and other species, partly because of the dissolution of nutrient salt from the brine layer. However, since the anoxic brine layer has demonstrated a rising tendency and the risk of blue tide and other fishery damage has increased in recent years, a variety of measures have been taken to control salinity intrusion into the Abashiri River.

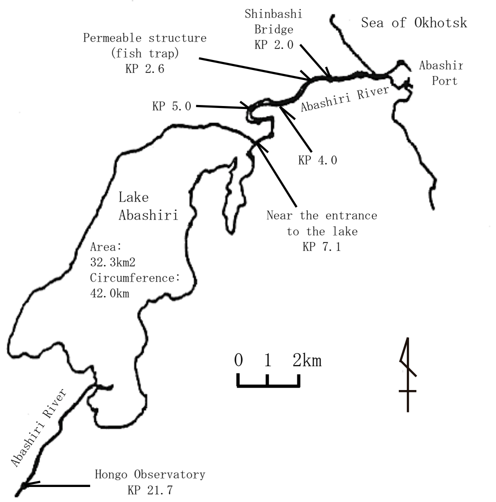


Figure 1 Schematic map of the area around the Abashiri River and Lake Abashiri

Past measures to control such intrusion have included installing weirs[1)] and shooting bubbles in the transverse direction of rivers[2)], both of which are considered very effective. However, there is still concern about safety in times of flooding, burdens on the river environment and maintenance/management of equipment. As a result, the use of a fish trap (a structure installed to catch salmon) is being considered in the Abashiri River as a permeable structure to control salinity intrusion. This measure can be as effective as conventional methods. **Photo 1** shows the installation condition of the fish trap.

The authors considered fish traps as permeable structures, and examined their behavioral characteristics by performing drag measurement experiments to obtain their drag coefficients, as well as salinity intrusion experiments to measure the salinity intrusion velocity in the presence of such structures[3)].

To enable comprehensive evaluation of the effects of permeable structures on salinity intrusion and flow in an actual river, a mathematical model of a one-dimensional, two-layered flow was also constructed, and the effects of the difference in permeability were examined based on the calculation results[4)]. However, while the validity of the mathematical model has been confirmed by comparing calculated values with those observed at high tide, the validity of calculation results over a longer period of time that includes low tide conditions has not been confirmed. It is also necessary to consider differences related to the position and number of structures installed in addition to the current examination of structures in terms of differences in permeability.

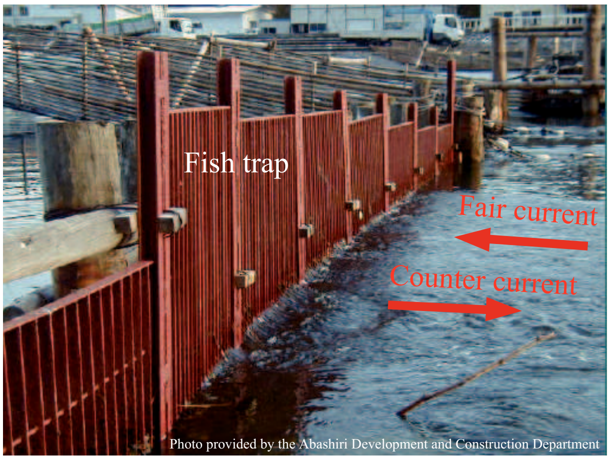


Photo 1 Installation condition of the fish trap in the Abashiri River (seen from the left bank)

In this study, numerical calculation was conducted for 20 days including high and low tides, and the results were compared with observed values to confirm the validity of the long-term calculation results.

2. Mathematical model

A mathematical model to evaluate the effects of permeable structures on salinity intrusion into an actual river was constructed based on a one-dimensional, two-layered flow model with a relatively small calculation load. The continuity equations for the upper and lower layers are as follows:

$$\frac{\partial h_1}{\partial t} + \frac{1}{B}\frac{\partial Q_1}{\partial x} = 0 \tag{1}$$

$$\frac{\partial h_2}{\partial t} + \frac{1}{B}\frac{\partial Q_2}{\partial x} = 0 \tag{2}$$

Since the density interface is used as the interface between the upper and lower layers in the mathematical model in this study, entrainment from the lower to the upper layer was ignored, and thus no equation on density was solved. The equations of motion are as follows:

$$\frac{\partial u_1}{\partial t} + u_1\frac{\partial u_1}{\partial x} + g\left(\frac{\partial h_1}{\partial x} + \frac{\partial h_2}{\partial x} - i_0\right) + g\left(i_{f1} + i_{fs} + i_{ft1}\right) = 0 \tag{3}$$

$$\frac{\partial u_2}{\partial t} + u_2\frac{\partial u_2}{\partial x} + g\left(\frac{\partial (1-\epsilon)\, h_1}{\partial x} + \frac{\partial h_2}{\partial x} - i_0\right) + g\left(i_{f2} + i_{fs} + i_{ft2}\right) = 0 \tag{4}$$

Where h is the water depth [m], Q is the flow rate [m^3/s], B is the river width [m], u is the flow velocity [m/s], i_0 is the riverbed slope, i_{f1} and i_{f2} are the friction slopes, i_{fs} is the drag term of the permeable structure, i_{ft} is the interfacial form drag term, x is the longitudinal distance [m], t is the time [s], subscript 1 is the upper layer (freshwater layer) and subscript 2 is the lower layer (brine layer).

2.1 Frictional resistance

Kaneko's formula[5)] was used to find the interfacial drag coefficient f_i from the product of the Froude and Reynolds numbers of the upper layer, and Manning's coefficient of roughness n was used for the drag coefficient of riverbed roughness.

$$f_i = 0.2 \times (R_e F_d^2)^{-0.5} \tag{5}$$

$$f_b = \frac{2gn^2}{h_2^{1/3}} \tag{6}$$

Where $R_e = \frac{u_1 h_1}{\nu}$, $F_d = \frac{u_1}{\sqrt{\epsilon g h_1}}$. The friction gradients i_{f1} and i_{f2} were included in the equations of motion as presented below.

$$i_{f1} = \frac{f_i}{2gh_1}(u_1 - u_2)|u_1 - u_2| \tag{7}$$

$$i_{f2} = \frac{f_b}{2gh_2}u_2|u_2| - \frac{f_i}{2gh_2}(1-\epsilon)(u_1 - u_2)|u_1 - u_2| \tag{8}$$

2.2 Resistance of permeable structures

To evaluate the effect of differences in the permeability of structures on salinity intrusion, the drag terms of the equations below were added to the respective equations of motion for the upper and lower layers.

$$i_{fs} = \alpha \frac{C_D}{2g\Delta x} u|u| \tag{9}$$

$$\alpha = 1 - \frac{\gamma}{100} \tag{10}$$

Where C_D and γ are the drag coefficient and permeability [%] of the structure, respectively. The mean value of C_D=1.41 was found from drag measurement[3).

2.3 Interfacial form drag

While a one-dimensional, two-layer flow is generally considered effective for analysis of moderately mixing saline wedges, it is rarely used for strongly mixing saline wedges due to the discontinuity of the interface shape at the tip, among other reasons. This is because the steep interfacial gradient at the tip is a primary problem.

The authors have therefore conducted studies on analysis methods based on a one-dimensional, two-layer flow mathematical model to produce moderately to strongly mixing saline wedges. It is considered possible to solve the problem of the steep interfacial gradient at the tip of a strongly mixing saline wedge by introducing its form drag, which is presumed to be the function of the projected interfacial area. In this function form, the form drag becomes smaller when the interfacial gradient is gentle, as in the case of a weakly mixing saline wedge, and larger when the gradient is steep, as in the case of a strongly mixing saline wedge.

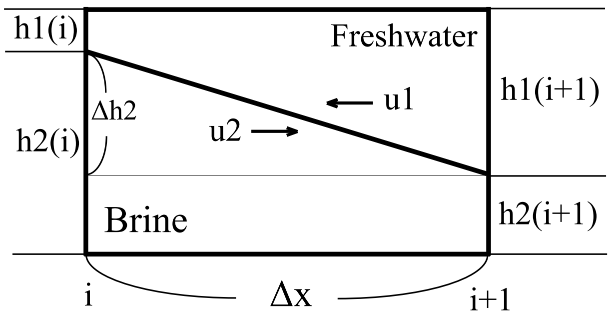


Figure 2 Schematic diagram of interfacial form drag

In this study, the proportionality of the form drag of this interface to the projected interfacial area and the relative velocity of freshwater and brine was taken into consideration in the form expressed by the equations below. **Figure 2** shows a conceptual diagram of interfacial form drag, where $\frac{\Delta h_2}{\Delta x}$ represents the interfacial gradient.

$$i_{ft1} = \frac{if_t}{2gh_1}\frac{\Delta h_2}{\Delta x}(u_1 - u_2)|u_1 - u_2| \tag{11}$$

$$i_{ft2} = -\frac{if_t}{2gh_2}\frac{\Delta h_2}{\Delta x}(u_1 - u_2)|u_1 - u_2| \tag{12}$$

Where if_t is the form drag coefficient of the interface and is given as if_t=1.22, with which the error becomes the smallest at the tip of the interface in both the experiment and the calculation.

2.4 Calculation conditions

In the river channel used for calculation, each section of the mean riverbed height and river width was treated as a rectangular cross section based on the transverse data obtained in a survey in 2000.

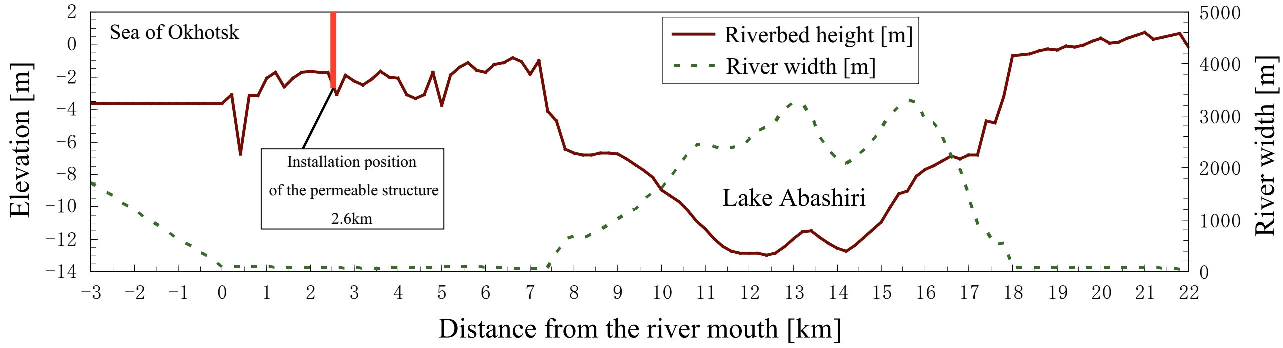


Figure 3 River channel conditions for numerical calculation

Figure 3 displays the calculation section, riverbed height and river width. The calculation area was a 25-km section between -3 km and 22 km. The calculation period was 20 days (48 hours) between 0:00 on June 6 and 0:00 on June 26, 2006, which included both high and low tides. During this time, the water period and salinity concentration were observed on site. The boundary conditions were the flow rate of freshwater per unit width at the upstream edge and the tide level at the downstream edge. **Figure 4** presents the boundary conditions.

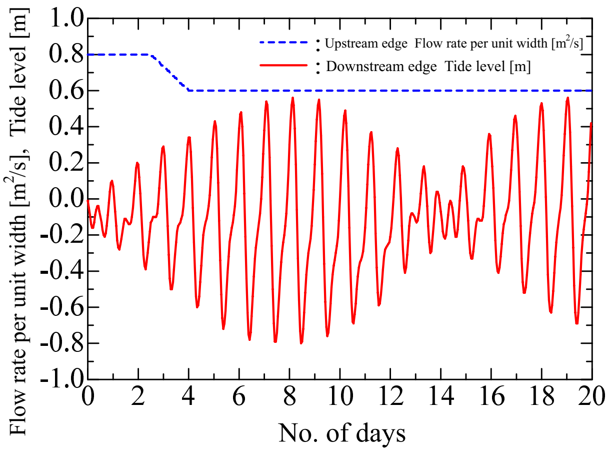


Figure 4 Boundary conditions (between 0:00 on June 6, 2006 and 0:00 on June 26, 2006)

The flow rate of freshwater per unit area was adjusted in the upstream area to make the observed and calculated values of salinity concentration identical, because the flow rate per unit area for tributaries flowing into Lake Abashiri was not taken into account in the calculation. The flow rate of brine per unit width at the upstream edge was given as a uniform value of q_2=0.0[m^2/s].

The brine depth at the downstream edge was the limit inner depth expressed by the equations below[6], and the freshwater depth was found from the difference between the tide level and the brine depth. In the calculation, the possible brine depth and the lowest freshwater depth were both assumed to be 1 mm.

$$h_2 = HZ - h_1 - Z \tag{13}$$

$$h_1 = F_{io}^{2/3} \times (HZ - Z) \tag{14}$$

$$F_{io} = \frac{q_1}{\sqrt{\epsilon g (HZ - Z)^3}} \tag{15}$$

Where h_1 is the depth of the freshwater layer at the downstream edge [m], h_2 is the depth of the brine layer at the downstream edge [m], HZ is the tide level [m], Z is the riverbed height at the downstream edge, and q_1 is the flow rate per unit width of the freshwater layer at the downstream edge [m^2/s].

A point 3 km seaward from the mouth of the Abashiri River was set as the downstream edge on the assumption that this was the point at which the second power of the density Froude number was 1 (a condition for a river mouth with density flow). The water temperature was assumed 15 ℃ for both freshwater and brine based on observation data, and the salinity concentration was set at 2 psu for freshwater and 25 psu (the mean concentration of the sea (30 psu) and Lake Abashiri (20 psu)) for brine. Manning's coefficient of roughness is very important, since it has a dominant influence on the hydraulic quantity. The method of Kishi and Kuroki[7), 8)] was used to calculate Manning's coefficient depending on changes in hydraulic quantity in advance based on the energy gradient, water depth and particle size. The mean particle size was found to be 24 mm from the observation data.

The coefficient of roughness used for calculation was $n = 0.017$, which was the mean value of the calculation section and period found in advance. Since the measured elevation of the interface between the freshwater and brine layers of Lake Abashiri was approximately -4 m, the layer below this level was regarded as brine in the initial condition. The calculation section interval Δx=20[m] and the calculation time step Δt were calculated using the equation below to satisfy the CFL condition.

$$\Delta t = \frac{C_r \Delta x}{u_{max} + \sqrt{g h_{max}}} \qquad (16)$$

Where u_{max} is the maximum flow velocity of freshwater or brine in the calculation section at a certain hour [m/s], h_{max} is the maximum depth of freshwater or brine in the calculation section at a certain hour [m], and C_r is the Courant number (C_r=0.06).

3. Validity of the mathematical model

To confirm the validity of the calculation results over a long period, numerical calculation was conducted for 20 days (between 0:00 on June 6 and 0:00 on June 26, 2006) including high and low tides, and the results were compared with the observed values. A period when fish traps were removed and the flow rate fluctuation from the upstream area was small was selected to simplify the calculation.

3.1 Comparison of observed and calculated values

The salinity concentration and water level values observed at intervals of ten minutes in four sections (KP2.5, 4.0, 5.0 and 7.1) between the mouth of the river and the entrance to the lake were used as the observed values. **Figures 5, 6** show a comparison between the values observed in these four sections and the calculated values by salinity concentration and water level, respectively. Since the salinity concentration was observed 50 cm below the water surface, the calculated salinity concentration value was 2 psu if this position was in the upper layer, and 25 psu if it was in the lower layer.

Looking at the horizontal axis of **Figure 5a)**(which shows the observation values of salinity concentration at KP2.5), the duration of salinity intrusion was longer at high tide than at low tide, but became shorter in the upper reaches from the observation values displayed in **Figures 5b), c), d)**. The calculated and observed values correspond well with each other for the duration of intrusion and the beginning and end of intrusion at both high and low tides.

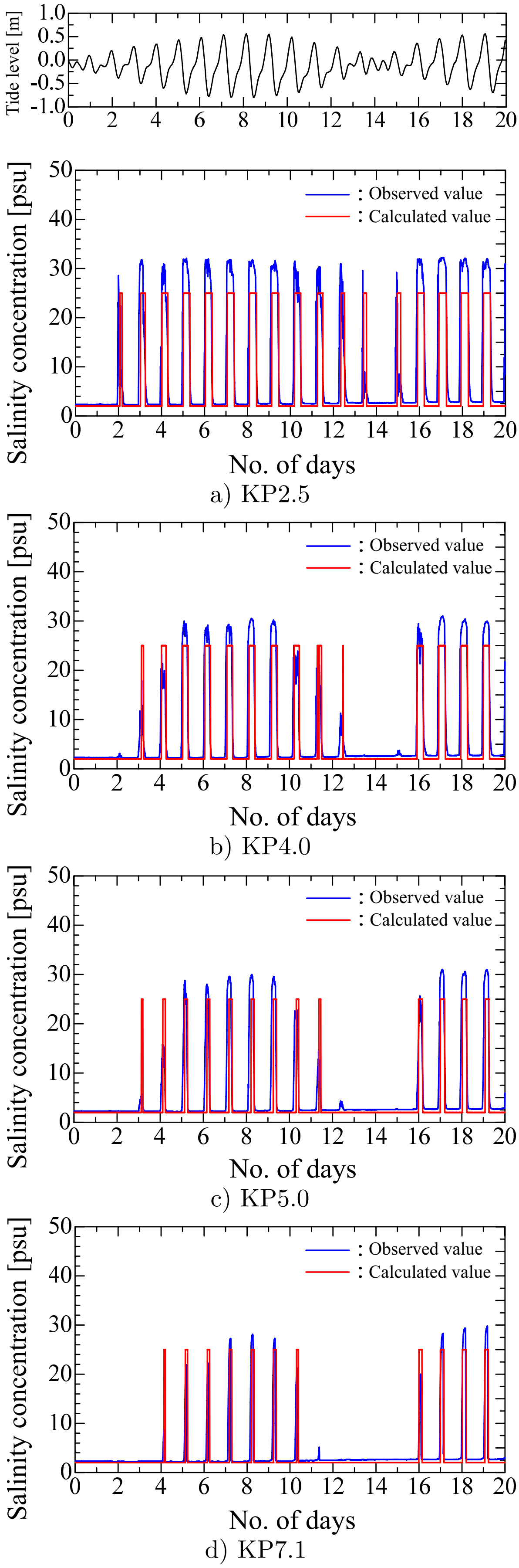


Figure 5 Observed and calculated salinity concentration values

In **Figure 6a)**, the observed water levels at KP2.5 correspond well with the calculated values. In **Figures 6b),c)**, the calculated water levels during the low tide period were lower than the observed values, although those in the incoming, high and falling tide periods corresponded with each other. In **Figure 6d)**, the calculated water levels in the calculation period were lower than the observed values, with an average difference of 7.8 cm. In particular, the water levels were lower at low tide than at high tide. The calculated levels at KP4.0 and 5.0 became too low at low tide. This was probably because the assumed roughness was too small compared with that of the points on the actual site, or because the roughness increased at low tide as an effect of the meandering river channel. However, since the cause has not been clarified, studies including field observation data will be necessary in the future. The low calculated water levels at KP7.1 in **Figure 6d)** probably occurred because the flow rate per unit width given at the upstream edge was too small. Although some problems concerning water level still remain as outlined above, the long-term calculation results of the mathematical model constructed in this study were considered valid in terms of salinity intrusion. This is because the focus of this paper is on the presence of salinity intrusion into Lake Abashiri, and the duration as well as the beginning and end of intrusion corresponded well at different positions.

4. Control effect of permeable structures

This section clarifies the salinity intrusion control effect by changing the permeability, position and number of permeable structures for the same period as that of the previous section (20 days between 0:00 on June 6 and 0:00 on June 26, 2006) using the mathematical model constructed in this study. In this paper, permeability refers to the ratio (%) of the area of water holes in the structure to the cross-sectional area of the running water. As an example, if the water running rate is 80%, 20% of the flow area is that of the structure, and the other 80% is that of water holes.

4.1 Difference in effect from differences in permeability

Calculation was performed by changing the permeability of structures to 20, 40, 60, 80 and 100%. **Figure 7a)** presents the cumulative value of salinity intrusion into Lake Abashiri at each level of permeability. The cumulative value was found from

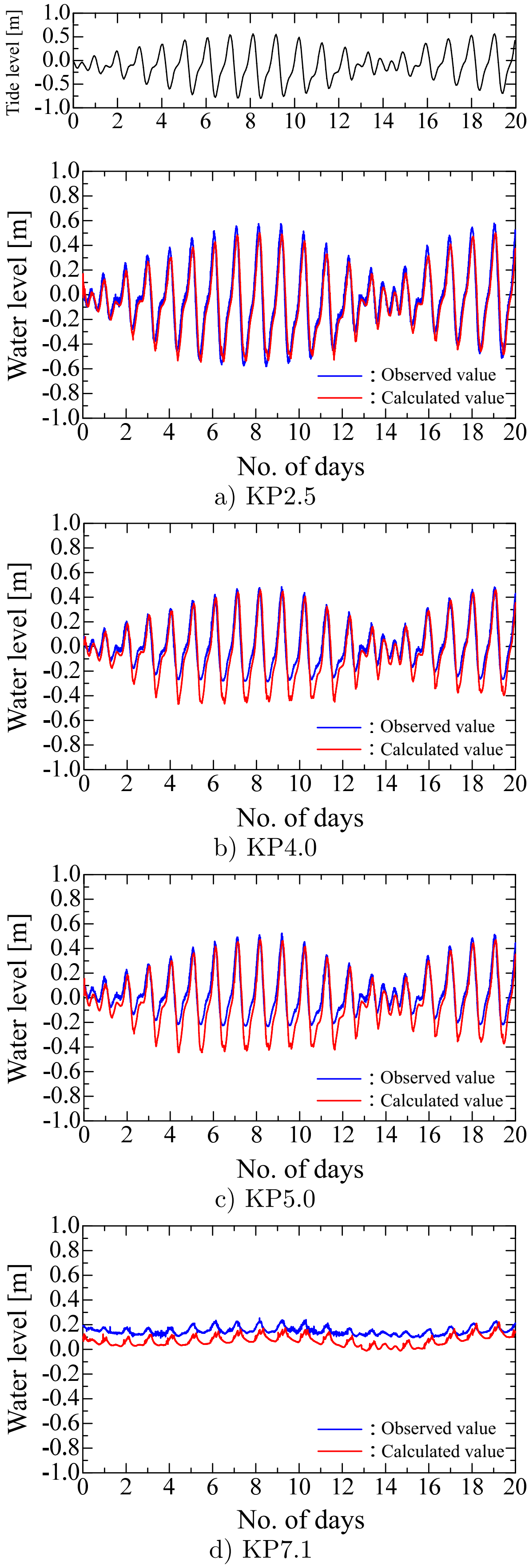


Figure 6 Observed and calculated water level values

the flow rate, Δt and salinity concentration.

Figure 7a) shows that salinity intrusion into Lake Abashiri occurred at high tide but not at low tide. Since the difference in inflow salinity by permeability cannot be clarified by comparing cumulative values, salinity controlled for each permeability level is presented on the vertical axis of **Figure 7b)** based on 100% permeability (i.e. a case without a structure). Salinity on the vertical axis was calculated as [inflow salinity for each permeability level] - [inflow salinity for 100% permeability], and the negative direction (the downward direction in the figure) represents a higher salinity control effect. It can be seen from the figure that the salinity intrusion control effect was greater when structures had finer meshes.

Compared with cumulative salinity intrusion into Lake Abashiri in the case without a structure (100%), the rate of intrusion in cases with structures was 97.3% (20% permeability), 97.7% (40%), 98.5% (60%) and 99.3% (80%). The numerical calculation results in this study revealed that the salinity intrusion control effect was higher for structures with finer meshes, and that the degree of the effect could be evaluated quantitatively.

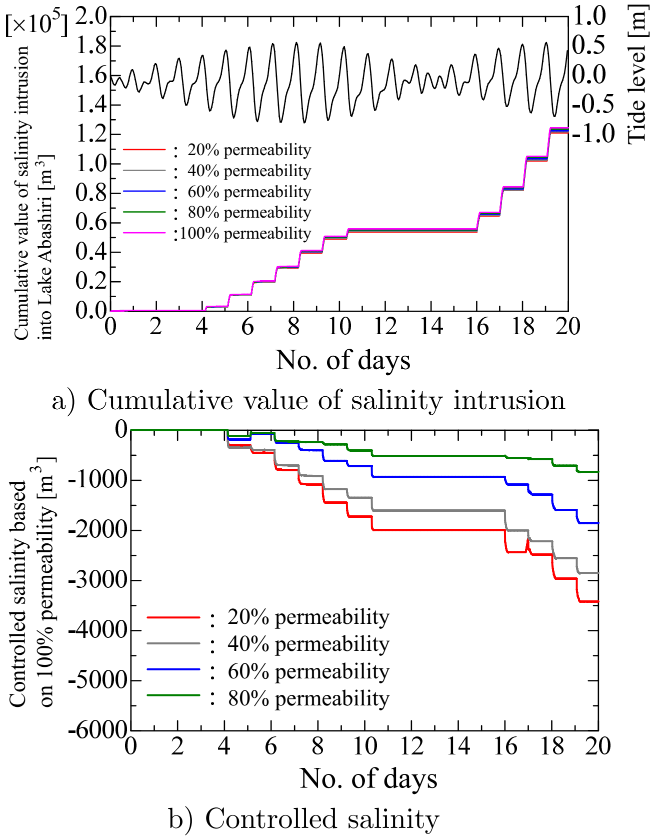


Figure 7 Control effect of permeable structures by differences in permeability

4.2 Difference in effect from differences in installation position

To clarify the difference in the salinity intrusion control effect from differences in the installation position of permeable structures, numerical calculation was performed for 50% permeability and by changing the positions to KP2.6, 3.0, 4.0, 5.0, 6.0 and 7.0. **Figure 8a)** displays the cumulative values of salinity intrusion into Lake Abashiri for each installation position.

Since the difference in inflow salinity by position could not be clarified by comparing the cumulative values in **Figure 8a)**, the controlled salinity in each section was presented on the vertical axis of **Figure 8b)** based on the installation position at the actual site (KP2.6). Salinity on the vertical axis was calculated as [inflow salinity at each position] - [inflow salinity at KP2.6], and the negative direction (the downward direction in the figure) represents a higher salinity control effect.

It can be seen from **Figure 8b)** that the salinity intrusion control effect increased when structures were positioned upstream, except at KP5.0. The position of KP5.0 was examined. The mean riverbed height at KP1.0 to 4.8 was -2.21 m, and that at KP5.2 to 7.0 was -1.37 m, a difference of 84 cm. Since the mean riverbed height at KP5.0 was -3.77 m and longitudinally lower, KP5.0 was

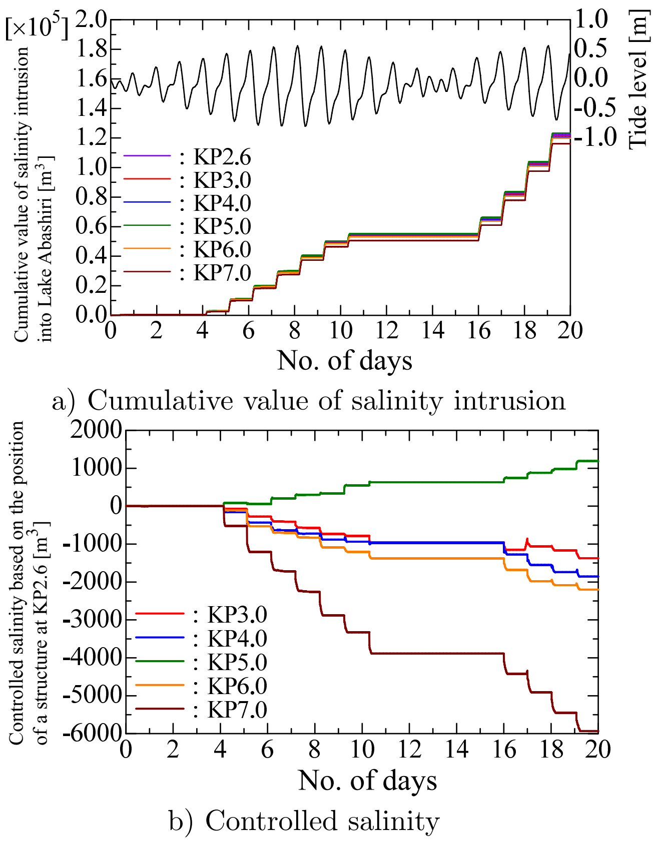


Figure 8 Control effect of permeable structures (50% permeability) by differences in number

judged to be a section with a large water surface gradient. It was presumed that, when structures were positioned at KP5.0, salinity inflow was restricted at high tide since the water surface gradient became even greater than the case with no structure, and salinity outflow was restricted at low tide since the upstream water level increased and flow velocity decreased due to the resistance of the structures. It was thus presumed from the calculation results that salinity outflow was restricted even more than its inflow, and that the installation of structures at KP5.0 resulted in a lower salinity intrusion control effect.

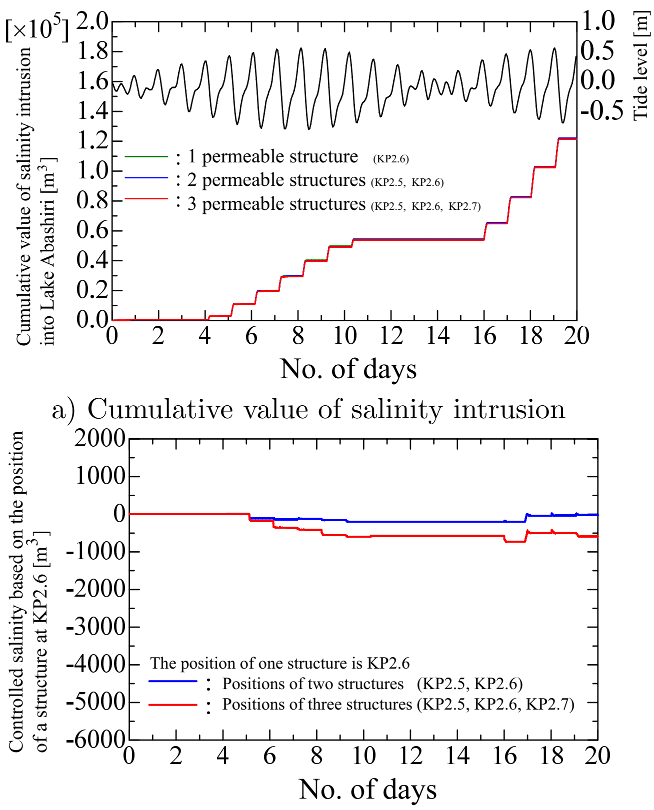
The salinity intrusion control effect of structures was 98.9% (KP3.0), 98.5% (KP4.0), 101.0% (KP5.0), 98.2% (KP6.0) and 95.1% (KP7.0) compared with the values for cumulative salinity intrusion into Lake Abashiri in the case of the installation position of KP2.6 (100%). The numerical calculation results of this study revealed that the salinity intrusion control effect increased when structures were positioned upstream except in the case of installation at KP5.0, and that the degree of the effect could be evaluated quantitatively.

4.3 Difference in effect from differences in the number of structures

To clarify the difference in the salinity intrusion control effect from differences in the number of permeable structures, numerical calculation was performed for 50% permeability, changing their number to 1 (KP2.6), 2 (KP2.5, 2.6) and 3 (KP2.5, 2.6 and 2.7). **Figure 9a)** presents the cumulative values of salinity intrusion into Lake Abashiri for different numbers of structures.

Since the difference in inflow salinity by the number of structures could not be clarified by comparing the cumulative values in **Figure 9a)**, the controlled salinity by number was presented on the vertical axis of **Figure 9b)** based on the values for one structure (KP2.6) at the actual site (KP2.6). Salinity on the vertical axis was calculated as [inflow salinity for each number] - [inflow salinity with one structure], and the negative direction (the downward direction in the figure) represents a higher salinity control effect.

It can be seen from **Figure 9b)** that the salinity intrusion control effect increased when the number of structures was greater. While the control effect of two structures was almost the same as that of one structure on the 20th day, the effect was greater between the 5th and the 17th days. However, the controlled salinity on the vertical axis of **Figure 9b)** is in the positive direction on the 17th day, indicating that the salinity intrusion control effect of two structures was smaller than that of one structure. It can be presumed from the calculation results that the effect of two structures became smaller than that of one structure due to the hydraulic quantity conditions on the 17th day, since salinity outflow was restricted by two structures even though the inflow was also restricted.



a) Cumulative value of salinity intrusion

b) Controlled salinity

Figure 9 Control effect of permeable structures (50% permeability) by differences in position

The salinity intrusion control effect of structures was 99.98% (2 structures) and 99.5% (3 structures) compared with the cumulative salinity intrusion into Lake Abashiri in the case with one structure (100%). The numerical calculation results of this study revealed that the salinity intrusion control effect increased when the number of structures was increased, and that the degree of the effect could be evaluated quantitatively.

From the results of examining the position and number of structures, it can be said that the salinity intrusion control effect was greater when structures were positioned upstream than when the number of structures was increased, as shown in **Figure 8b)** and **Figure 9b)**.

5. CONCLUSION

This study produced the following findings:

1) To confirm the validity of long-term calculation results, numerical calculation was performed for 20 days including low and high tides, and the calculated values were compared with observed values. The values corresponded well with each other in terms of the duration of strongly mixing salinity intrusion and the start and end of intrusion, indicating the validity of the calculation results for salinity intrusion obtained by the numerical model constructed in this study.

2) The numerical calculation results in this study revealed that the salinity intrusion control effect increased when the permeable structures had finer meshes and were positioned upstream (except when they were positioned 5 km from the estuary and when the number of structures was greater). The controlling effect of positioning the structures upstream was also greater than that of increasing their number.

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