Adaptation to Salinity Change Induced by Sea-Level Rise in Hinuma Lake, Japan

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1. INTRODUCTION

Brackish water lake is home of peculiar organisms, as its salinity is middle of those of sea and fresh water. Its salinity changes sensitively with sea level, river flow rate and lake topography. Hinuma Lake is one of brackish water lakes in Japan and connects with the Pacific Ocean through a tributary and a major river. Therefore the inflow process of salt water to the lake is very complex. The purposes of this study are to estimate impact of sea-level rise on the lake salinity and to examine adaptation options to preserve ecosystem against the impact. To this end, we carried out a long-term observation on the inflow of sea water and seasonal change of salinity to understand the mechanism of sea water intrusion and to verify the numerical simulation model. The influence of topographic changes on salinity is also investigated for the last five decades.

2. FEATURE OF HINUMA LAKE

Hinuma Lake is located about 80 km north of Tokyo in Japan. Figure 1 shows the topography of Hinuma river basin. This lake connects with Pacific Ocean through a tributary Hinuma River (8 km), and the main stream, Naka River (0.5 km). The flow rate of Naka River is ten times as large as that of Hinuma River; which means that the salt water intrusion to the lake is mainly governed by Naka River. The water depth profile of Hinuma River is shown by Fig. 2 which is strongly irregular. The lake is shallow, 2 m in average, and shallower around lake head and mouth.

Fresh water clam, Corbicula japonica Primes, is surviving in the Hinuma basin. The number of the clam has, however, been decreasing for the last

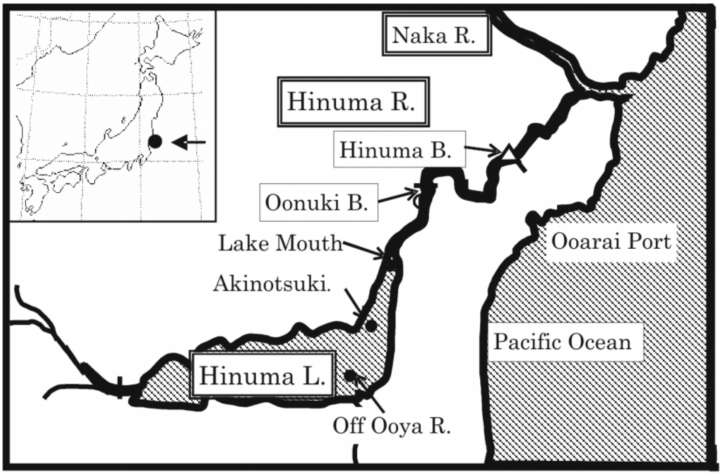

Figure 1: Hinuma river basin.

two decades. The citizens and fishermen attribute it to salinity decrease by the change of water depth in the downstream of Hinuma River, and land reclamation around the lake mouth.

3. PROCESS OF SALT WATER INTRUSION

Vertical distributions of salinity from the junction of the two rivers to the lake were measured in different tidal phases by manual salinometers from a ship. The self-registering salinometers measured temporal change of salinity at five points shown by Fig. 2 during one year, which was implemented by the cooperation between Ibaraki University, National Research Institute of Fisheries Engineering and Ibaraki Prefecture Inlandwater Fisheries Institutes. The self-registering salinometer at 11.5 km point implemented by Ibaraki Prefecture Inlandwater Fisheries Institutes has been working from August 1997.

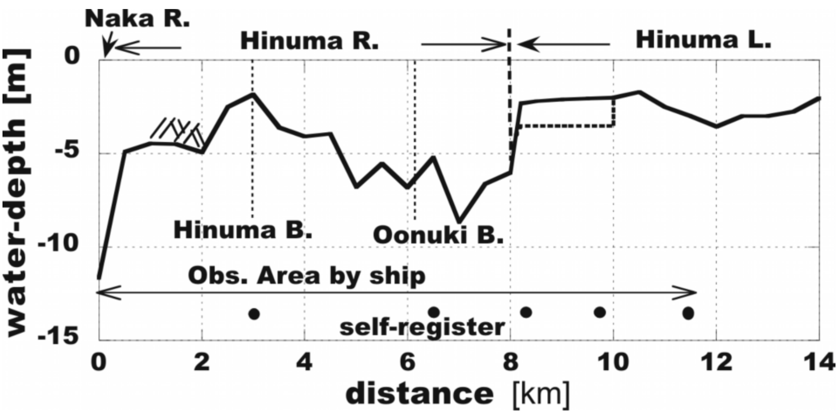

Figure 2: Longitudinal section of Hinuma river.

Strong salt water instrusions were observed on December 19, 2002 as shown in Fig. 3. Figures 3(a), (b) and (c) show the results in the end of first flood tide phase, weak ebb tide phase and next flood tide phase respectively.

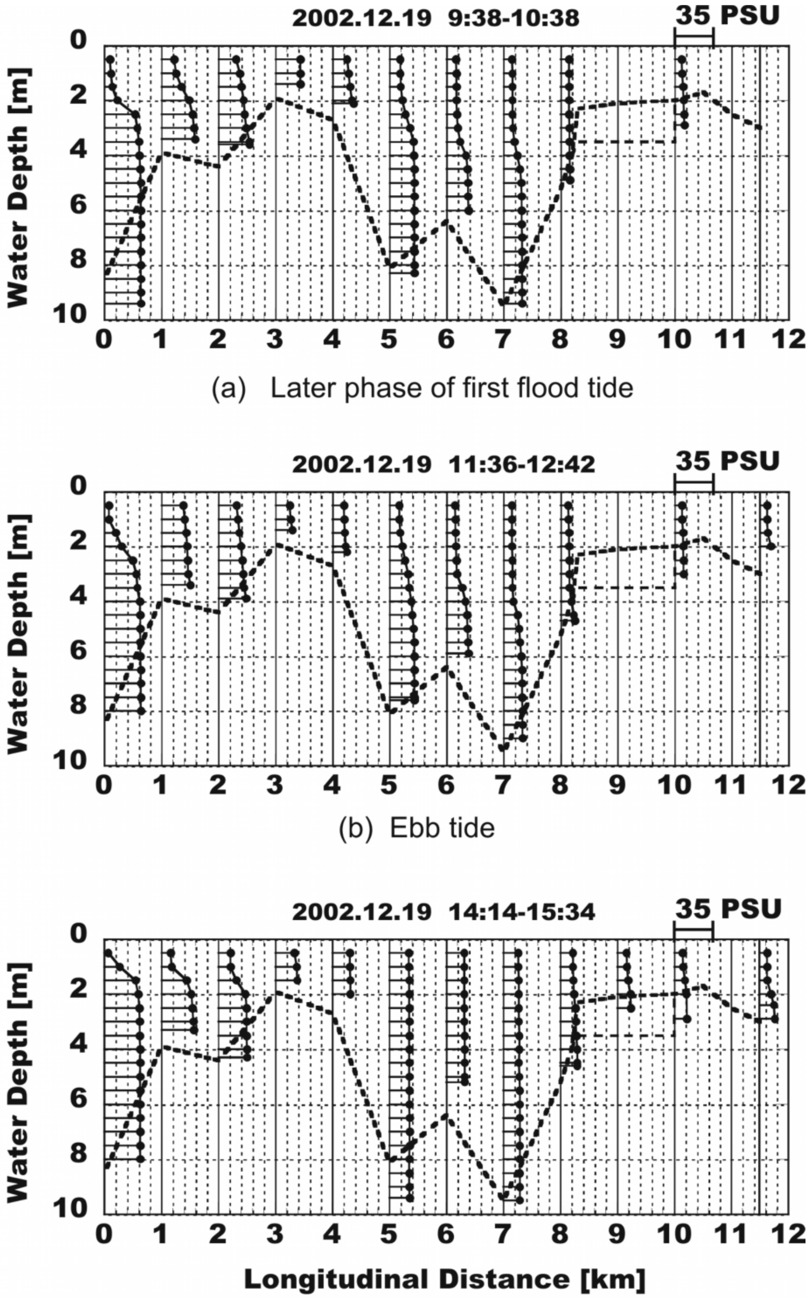

Figure 3: Salinity distribution around Hinuma river.

Salt waters start to flow into the tributary after the halocline interface in Naka River becomes higher than the bottom level of the tributary (Fig. 3(a)). This is usually delayed a few hours after the initial phase of the flood tide. The vertical profile of salinity becomes partially mixed-type at the downstream side. On the other hand, the profile changes to uniform when the salt water mass passes a quite shallow portion 3 km upstream from the junction. This salt water stalls at a deep region between 4 and 8 km and cannot further intrude into the lake in a single tide period, 12 hours. In the following ebb tide phase (Fig. 3(b)), the salt water body in this deep region has been stalled and the upper part of water body returns to downstream. The vertical profile in downstream side from 3 km becomes stronger mixed-type than that in the previous flood tide phase. In the next flood tide (Fig. 3(c)), new salt water body which is strong mixed-type comes in this deep region, and the previous salt water body stalled in this deep region intrudes to the lake. The observed results on the other day when the tidal range was large was also same as these dynamic process. When the tidal range was small, the horizontal length of the process was short and a salt water body did not intrude to the lake. A large salt water body intrudes to the centre on the Lake about ten times only in a year (Fig. 4). Figure 5 shows the temporal change of the active salinity intrusion from the lake mouth to the centre region of lake in November 2002. The observed 6.4 km point is in the tributary, the 8.2 km and 10 km point are shallow water depth around the lake mouth and the 11.7 km point is the entrance of the centre part. The periodical fluctuation of salinity following the tidal fluctuation occurred up to the shallow region, the 10 km point. When a large amount of salinity is supplied at lake mouth, the 8.2 km point, this salt water body infiltrates to the centre part of lake through the 10 km point. The remarkable phenomenon is time lag of salinity fluctuation

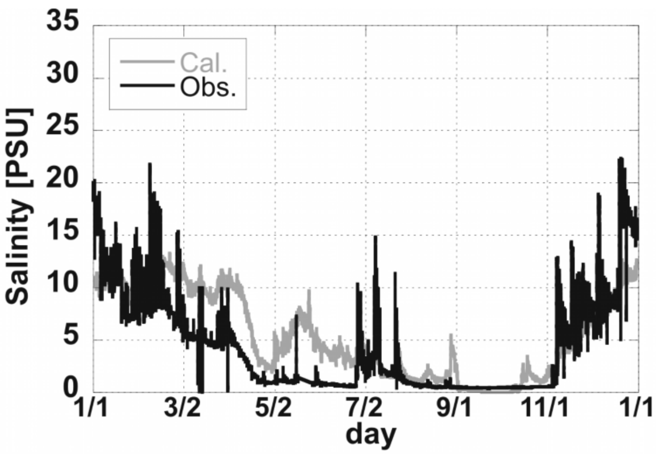

Figure 4: Salinity in Hinuma lake.
(The observed data are provided by Ibaraki Prefecture Inlandwater Fisheries Institutes)

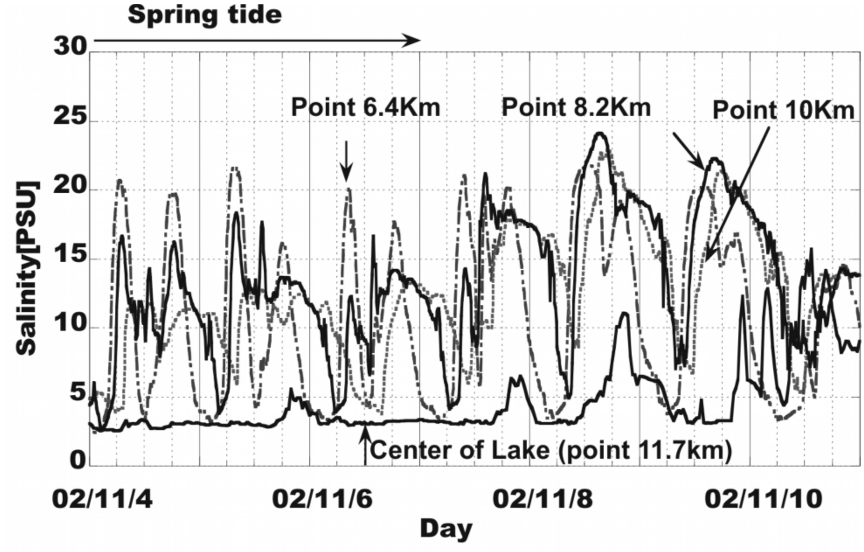

Figure 5: Temporal change of salinity into Hinuma lake.
(The observed data at Point 6.4 and 8.2 provided by National Research Institutes of Fisheries Engineering, Japan)

between the 8.2 km to 10 km point when the salt water body intrudes. The lag is a few hours. As water surface fluctuation in the lake is delayed three hours on comparing with that at the Ooarai port in Pacific Ocean, the time lag of salinity is not the phase difference of tide waves. These results indicate that the shallow water depth topography around the lake mouth act as a filter obstructing the salinity infiltration, i.e., the topography change the salinity dynamics from continuous to intermittence phenomena.

4. THREE DIMENSIONAL FLOW MODEL

The present model consists of two sub-models for flow field and density field, which are almost same as the model adapted to Tokyo bay in Japan by Mimura et al. (1998). The governing equations of flow model are continuity and momentum equations (Equations 1 and 2) and that of density model is diffusion equation of salinity (Equation 3).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}=-\frac{g}{\rho}\frac{\partial \rho\eta}{\partial x}-fv+\frac{\partial}{\partial x}\left(A_x\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_y\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_z\frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial s}{\partial t}+\frac{\partial su}{\partial x}+\frac{\partial sv}{\partial y}+\frac{\partial sw}{\partial z}=\frac{\partial}{\partial x}\left(K_{\mathrm{x}}\frac{\partial s}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{\mathrm{y}}\frac{\partial s}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{\mathrm{z}}\frac{\partial s}{\partial z}\right) \quad (3)$$

In the above equations u, v and w are velocity in x, y and z direction, h and η are water depth and water surface elevation, S is salinity, and g, ρ and f are gravity acceleration, water density and Coriolis coefficient.

The improved parts of the model compared with the previous model were that Symmetric SOR method and Donor Accepter method are employed to solve the governing equation of flow model to reduce the numerical error. Donor Accepter is a method combined with Central and up-wind difference scheme. The parameter of the combination ratio is an empirical variable to get the stable and precise solutions in each tide and river flux condition. As boundary condition, temporal records of tidal elevation at Oarai port near the river mouth in Pacific Ocean, flux rate at each river and those of wind stress were given from field observations implemented by Ibaraki prefecture and Ministry of Land, Infrastructure and Transport. No salinity measured data for this simulation exists so that the values were set as 35 PSU and 0 PSU at Ocean and river boundary, respectively.

Figure 4 also shows the capacity of salinity prediction by the model in the condition of present sea level. Calculated result is in a good agreement with observed data.

5. IMPACT OF SEA LEVEL RISE BY GLOBAL WARMING

The changes of salinity in the lake by sea-level rise were predicted by the model. Scenarios for sea-level rise were four cases as shown in Fig. 6; +9 cm (minimum), +50 cm (average) and +88 cm (maximum) following

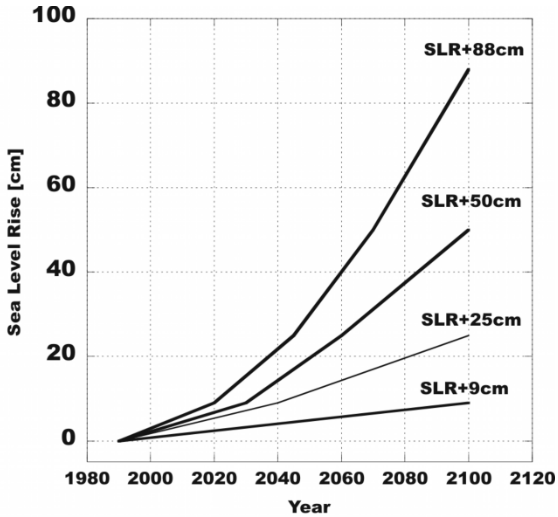

Figure 6: Four scenarios of sea level rise.

IPCC (2001) and + 25 cm which is the interpolation level. The target season was summer which is the spawning and growing season of the corbicula clam.

The calculated results of salinity at Off-Ooya River by each sea-level in 2100 are shown in Fig. 7. From the case +25 cm, the increase in salinity appears clearly. In the case +50 cm, the salinity rises much more not only along the tributary but also in the lake. The clam cannot survive under the high salinity of over 23 PSU (Nakamura, 1999), and even at present, they do not live in the ocean side from 3 km point from the junction because of this limit. Therefore, as sea-level rises, the living area of Corbicula will move upstream. In the case +88 cm, as the salinity above the bottom of the tributary almost becomes over 23 PSU, the clam will be able to live only in the lake.

The density of the average salinity below the water depth 2 m in the lake is taken for the significant salinity. This significant salinity is about 3 PSU lower than the results in Fig. 7. The temporal change of the significant salinity during sea level rising is shown in Fig. 8. The difference by the scenario of the sea level rise will appear gradually after 2020, and will become clear in about 2050. The influence of the sea level rise will not be able to be confirmed in a minimum scenario (SLR+9 cm in 2100).

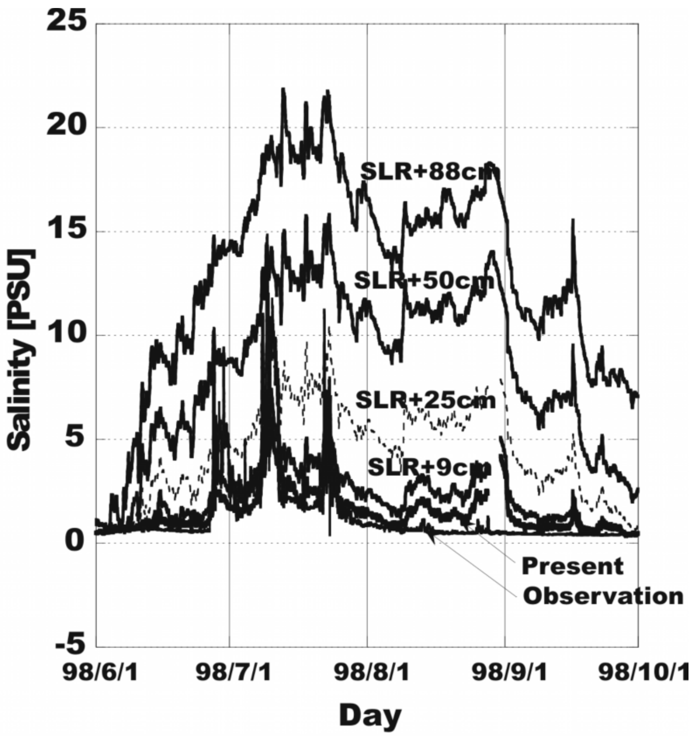

Figure 7: Impact of sea level rise.

The large change of the rate of discharge of fresh water in every year influences inflow rate of salinity very much. Table 1 shows the month-averaged salinity in the lake for five years. The difference between maximum and minimum salinity is about 9 PSU and the standard deviation of the salinity is about 4 PSU.

Table 1: Mean salinity in June at Off-Ooya River
(Ibaraki Prefecture Inlandwater Fisheries Institutes)

Year	*1998*	*1999*	*2000*	*2001*	*2002*	*Average*	*Standard deviation*
Salinity [PSU]	3.29	1.77	1.83	10.99	5.32	4.643	3.83

To take account of this fluctuation, maximum or minimum salinity are estimated by following supposed equation,

$$S_{max}.S_{min} = S_{cal.}(1 \pm \frac{\sigma_{obs}}{\overline{S_{obs}}}) \tag{4}$$

in which σ_{obs} and $\overline{S_{obs}}$ are standard deviation and averaged salinity calculated from the observation data shown in Table 1, S_{cal} is calculated salinity by simulation model and S_{max} and S_{min} are predicted maximum and minimum salinity. The predicted salinity on each scenario is shown in Fig. 8. The solid, upper and lower dotted lines are the average, maximum and minimum salinity, respectively.

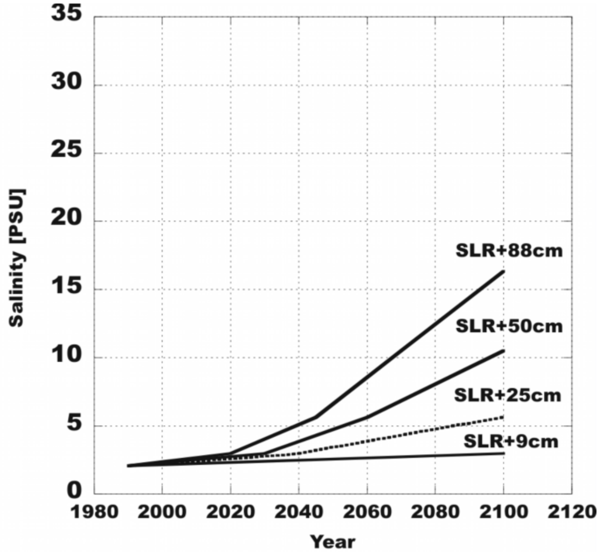

Figure 8: Temporary change of salinity in the lake by sea level rise.

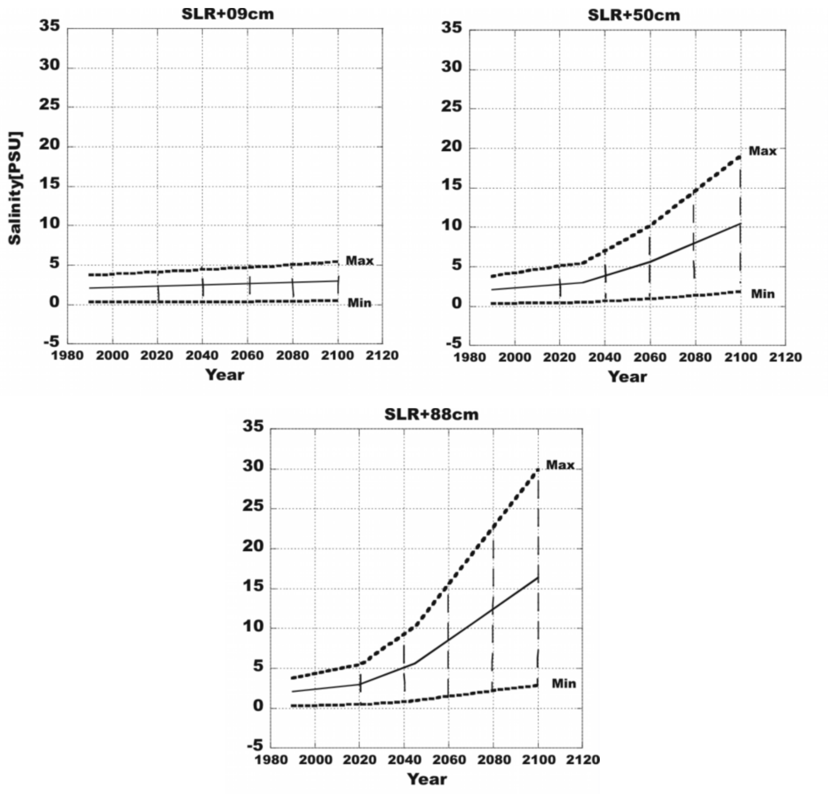

Figure 9: Temporal change of salinity in taking account of water discharge.

Though the difference between maximum and minimum salinity becomes large, we may be able to understand these results for the following reasons. When a large river flood occurred, there were no salt waters even in the river mouth because the width of the mouth in Naka River is only 200 m. On the other hand, when a water shortage occurred, salt water body arrived at the 15 km point in Naka River from the river mouth and at the 1.5 km upstream point from the lake. These results suggest us that we have to monitor the salinity rise induced by sea-level rise in taking account of these fluctuations, i.e., the effect of the flux rate of fresh water. For Hinuma basin, the evaluation term has to take 10 years which is the one cycle of the flux rate change induced by rain fall, or the evaluated salinity by sea level rise has to be calculated except the effect of the flux rate from observed salinity.

6. ADAPTATION TO SEA-LEVEL RISE

If we can raise the bottom of the river and lake in parallel to sea-level rise, salinity in this area will not change. However, as it is economically impossible to raise the bottom in all of the area, we should find the narrow sections for effective options of adaptation taking into account historical natural changes. In this study, the following four options were set;

Case A: The river bottom is raised at only the 3 km points in the tributary, where the water depth is shallowest in the river even at present. At this position, sands deposit naturally.

Case B: The artificial channel near the lake mouth is reclaimed again to put it back to the natural elevation.

Case C: The maximum water depth from the junction points of both rivers to 3 km in the tributary is set as 4 m. It may take a long time to attain this topography naturally.

Case D: Only the bottom in the tributary close to the junction rises up. At this position, the bottom elevation often changes due to flood flow in the main stream.

Through an estuary, a complete barrier is effective only for shutting out the salt water. However, this structure has been generating large destruction of ecosystem in Japan. Therefore, this option was not adapted in this study.

Figure 10 shows the temporal change of salinity at Off-Ooya River for the adaptation of Cases A and B, and Fig. 11 shows the comparison of all the adaptation capacity. Although each case reduce the salinity a little, Case-A which is the bottom up at the shallowest point in the tributary was found to be most effective among all the options to prevent salinity change induced by sea-level rise in this lake. The salinity at the upstream side of lake was reduced well. To decrease the salinity density more in the basin while keeping the above concept, we will need to take the additional adaptation in the main stream, Naka River.

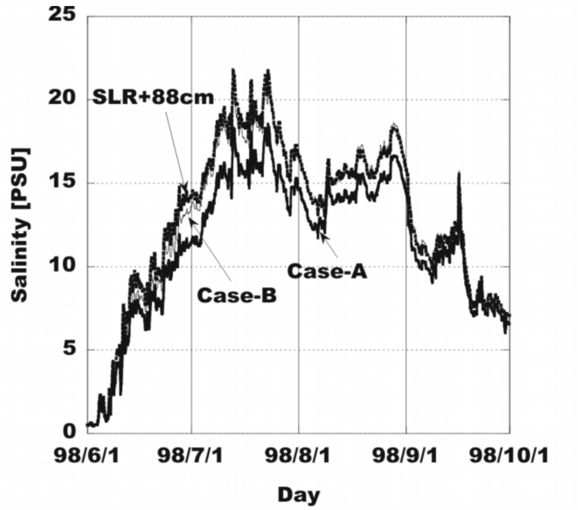

Figure 10: Effect of adaptation for salinity.

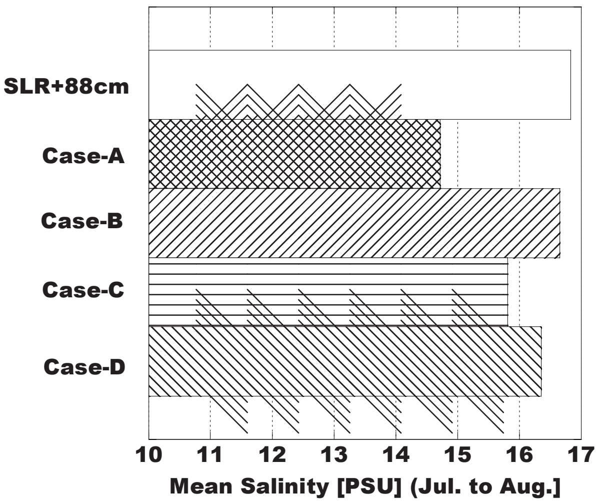

Figure 11: Comparison of salinity by adaptations.

7. CONCLUSIONS

The process of salt water body intrusion in Hinuma basin is complex due to the irregular water depth. The large salt water body is formed in the centre region of the lake only ten times in a year. The numerical simulation results, however, show that the body will intrude much according to the sea-level rise. Increasing salinity in the lake will appear after 2020 and become distinct around 2050. In the most critical scenario, which is +88 cm sea-level rise, the salinity in the tributary will become higher than the density for the clam to survive. For salt water instruction against sea-level rise, adapting the concept of historical natural change which maintains the natural process as best as possible, was not enough to reduce the salinity. Therefore, the present study suggests that we will need a support of natural power, for example natural topography change, to keep ecosystems against sea-level rise.

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