Simulation experiments for the remediation of hypolimnetic anoxia in Lake Nakaumi
- For the recovery of a sound ecosystem-

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1. Introduction

Lakes Shinji and Nakaumi are a coupled brackish lake system in Japan. Lake Shinji is the 6th largest lake in Japan, with a surface area of 79.2 km². Lake Nakaumi is the 5th largest lake in Japan with an area of 97.7 km². L. Shinji is connected to L. Nakaumi through the Ohashi river which is 7.7km in length. L. Nakaumi is connected with Japan Sea by the Sakai Channel which is 7.5km in length. These two lakes have very different hydrological characteristics. Seawater enters L. Nakaumi from the Japan Sea and because it is denser, it flows along the bottom of the lake to the mouth of R. Ohashi and forms the hypolimnetic layer. Less dense, brackish water from R. Ohashi flows into the lake and forms the surface layer. Therefore, a strongly differentiated two-layer system is formed in this lake. Salinity of the surface water is 14-20 psu and that of the bottom layer is 25-30 psu. In Lake Shinji, a halocline is usually not observed and salinity is 1-6 psu.

Both lakes have the same bathymetric character of a large surface area and shallow depth. However, the ecosystems of the two lakes are very different. In L. Shinji, a small bivalve, the Shijimi (Corbicula japonica) dominates in lake bottom and plays an important role in the nutrient cycle of the lake ecosystem. This shellfish is also the basis of an important fishery. On the other hand, the hypolimnion of L. Nakaumi becomes anoxic from April to October across most of the lake and the only benthic animals in the lake are in shallow waters during this half of the year. The healthy and productive ecosystem of L. Nakaumi was killed off by the reclamation works of the last 40 years.

Large commercial catches of marine products were recorded in L. Nakaumi until 1930, which was before the start of the reclamation project. Small bloody clam was a famous product from this lake just as L. Shinji was renowned for the Shijimi clam. Therefore, if oxic conditions can be restored in the hypolimnetic layer, the benthic organisms should re-colonize the lake floor, and a large fishery would be restored.

In this study, we examined the effects of restoration measures in terms of improving the oxygen levels in the hypolimnetic layer in L. Nakaumi using two existing models. This paper reports the results of these simulations.1)

2. Outline of simulation experiments

Two simulation models were used. One was the same model used to predict the effect of Honjo area reclamation works on water quality in L. Nakaumi by the Committee of Agriculture
The other is a physical-ecological interaction model made by Taguchi and Nakata. Both models are based on a 3D hydrodynamic model of the lake. The area of L. Nakaumi and L. Shinji was divided into small boxes, and the water quality was calculated for each box. In the first model, the area was divided into 1/3 km squares horizontally and into 8 layers vertically. In the second model, it was divided into 250–500m units horizontally and 1.5m units vertically (6 layers).

The first simulation experiment was carried out using the following conditions: 1) a 200 m section was removed from the Moriyama and Omisaki dikes, 2) construction of a tide dike (-3m) in place of the Nakaura tide gate in order to stop denser sea water from entering the lake, 3) filling in the deep hole created by dredging on the eastern side of the lake. The simulation also used environmental data from 1992.

The second simulation experiment was conducted by changing the second of the above three premises, i.e., instead of construction of a tide dike, the existing Nakaura tide gate was used, in addition a shallow littoral area was constructed in south-west part of the lake. The Nakaura tide gate has upper and lower gates which can be operated independently. In this simulation, only the lower gate was closed, and 20 m of middle section was opened for navigation. This simulation used environmental data from 1998. A third simulation was conducted with another change in the second simulation i.e. the Nakaura tide gate was closed during rising tides and open during falling tides.

3. Results

The first simulation experiment results are shown in Figs. 1 and 2. Fig. 1 shows the results of the no countermeasure case, i.e. the present state. In L. Nakaumi, dissolved oxygen in entering with sea water was consumed, and anoxic water developed during the summer over a large area of the lake including Yonago Bay. In L. Shinji, anoxia was predicted for the bottom layer in the central part of the lake in the summer. Fig. 2 shows the result after countermeasures were modeled, most importantly the construction of a shallow dike of -3m at Nakaura tide gate site. In the western part of the lake, DO concentration increased to 2–4 mg/l, and there was no anoxic layer. In the eastern part of the lake including Yonago Bay, however, DO concentrations were unchanged and an anoxic water layer still occurred. In the Honjo area, a strong halocline formed, but the simulation did not predict anoxia because of the rapid water exchange of this area. This result can be explained in the following way: dense sea water in the bottom layer of Sakai Channel did not enter L. Nakaumi due to the constructed tide dike, although a portion of the sea water entered the Honjo area. In the Honjo area, high salinities were predicted for the bottom layer, under 5m, although the salinity of the surface layer remained relatively low, predicted at about 14–18 psu. This surface water entered L. Nakaumi and the salinity of hypolimnetic water dropped, the density difference between surface and bottom layers became small, and the mixing of surface and bottom waters would occur easily.
The second simulation result is shown in Fig. 3 and the third one is shown in Fig. 4. The second simulation result is very similar to the first simulation experiment despite changes in the model and using environmental data from a different year, i.e. DO concentrations increased in western part of L. Nakaumi to about 2\textendash{}3mg/l. The result of third simulation shows little difference from the other two (Fig. 4), however DO concentration in the eastern part of the lake improved, i.e. DO concentration improved in all areas of the lake by about 1\textendash{}2mg/l and anoxia was prevented.

4. For the recovery of sound ecosystem

All simulation results showed significant improvements in the hypolimnetic conditions in the western part of the lake, where anoxic conditions disappeared throughout the year. This was achieved in simulations by repairing the depth of Nakaura Channel and cutting a part of the reclamation dike to restore pre-reclamation conditions.

Now we need to stop the reclamation project and start a dialogue on how to clean up the abandoned project. In the present plan, the Nakaura tide gate will be destroyed. However, I think it is better to consider the reuse of this gate. In the near future, it is predicted that sea level will be rise about 20\textendash{}100cm from its present elevation due to the green house effect. At that time, a new tide gate will be needed to protect L. Nakaumi from the intrusion of sea water. We therefore will need careful studies and discussions to decide on a course for the recovery of a sound ecosystem in Lake Nakaumi.

Reference

2) Agriculture Bureau of Chugoku and Sikoku area (1999): *Direction to use fishery in Honjo area*. (Japanese)
Fig.1 Simulation result in DO concentration in bottom layer in L. Nakaumi and L. Shinji in Aug. 1992. (the first simulation, no countermeasure)
図1．中海及び矢道湖における底層水の溶存酸素濃度分布の予測結果．現状（1992年8月の平均，第1モデルでの計算結果）

Fig.1 Simulation result in DO concentration in bottom layer after countermeasure (tide dike construction, cut a part of reclamation dike, filling up dredged hole). (the first simulation result)
図1．中海及び矢道湖における底層水の溶存酸素濃度分布の予測結果。対策あり（堤防の開削，浚渫窪地の埋め戻し）（1992年8月の平均，第1モデルでの計算結果）

Fig.3 Simulation result in DO change in bottom layer by countermeasure (close the lower gate of Nakaura tide gate). (the second simulation result)
図3．中浦水門下段ゲート締め切り条件での中海底層における溶存酸素の変化量（1998年8月，第2モデルでの計算結果）

Fig.4 Simulation result in DO change in bottom layer by countermeasure (operation of Nakaura tide gate). (the third simulation result)
図3．中浦水門操作条件での中海底層における溶存酸素の変化量（1998年8月，第3モデルでの計算結果）