Seasonal and areal features of the lagoonal environment in Lake Nakanoumi, a shallow coastal lagoon in Japan

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Keywords: coastal lagoon, salinity, brackish water, phytoplankton

Abstract

Lake Nakanoumi is a shallow coastal lagoon connected with the Japan Sea by a narrow channel. Over the past decade, land reclamation resulted in a 33% reduction of the lagoon's surface area. The remaining water basin of Lake Nakanoumi is scheduled to be artificially freshened to supply irrigation water for the newly reclaimed lands. This paper deals with the seasonal and areal features of the lagoonal environment prior to the beginning of the artificial desalinization.

Introduction

Coastal lagoons are areas of transition (ecotones) between freshwater and marine habitats, and they are the most vulnerable sectors of coastal water areas (Clark 1977). Since lagoonal environments are influenced by interactions between marine and terrestrial factors, they are hydrochemically complex and ecologically unique. Though there may exist many different lagoonal environments (Barnes 1980), few works deal with fertile shallow lagoonal environments in temperate Asia.

Many coastal lagoons have been subjected to a variety of man-made alterations including dyking, filling and pollution, since they are important commercially as harbors, recreational areas and most importantly for fisheries (Mee 1978). Nevertheless, there is a surprising lack of long-term survey data on lagoonal environment before and after a large-scale development project, and it is still difficult to assess properly the impacts of project now underway.

Lake Nakanoumi is a shallow coastal lagoon which is connected to the Japan Sea only by a narrow channel (Fig. 1). Over the past decade, land reclamation works have been carried out under the direct administration of the Ministry of Agriculture and Forestry with a resulting 33% reduction in the lagoon's surface area (Date 1978). The remaining water basin of Lake Nakanoumi is also scheduled to be artificially freshened (purified of its salinity) to supply irrigation water for the newly reclaimed lands. Since 1965 we have carried out monthly routine surveys on more than 20 physical, chemical and biological parameters at 12 permanent stations as part of a large study project desinged to assess the impact of the freshening works on the lagoonal environment. More than 200 000 routine data have been collected hitherto with respect to common physico-chemical and biological parameters, and it appears possible to make clear the spatial and temporal features of the lagoonal environment using some statistical techniques. This paper deals with the seasonal and areal features of this lagoonal environment prior to the beginning of the artificial desalinization. Needless to say, these before-impact data are valuable as a temporal control against which the after-impact data will be contrasted.

Hydrobiologia 97, 15–26 (1982). 0018-8158/82/0971-0015/$02.40.

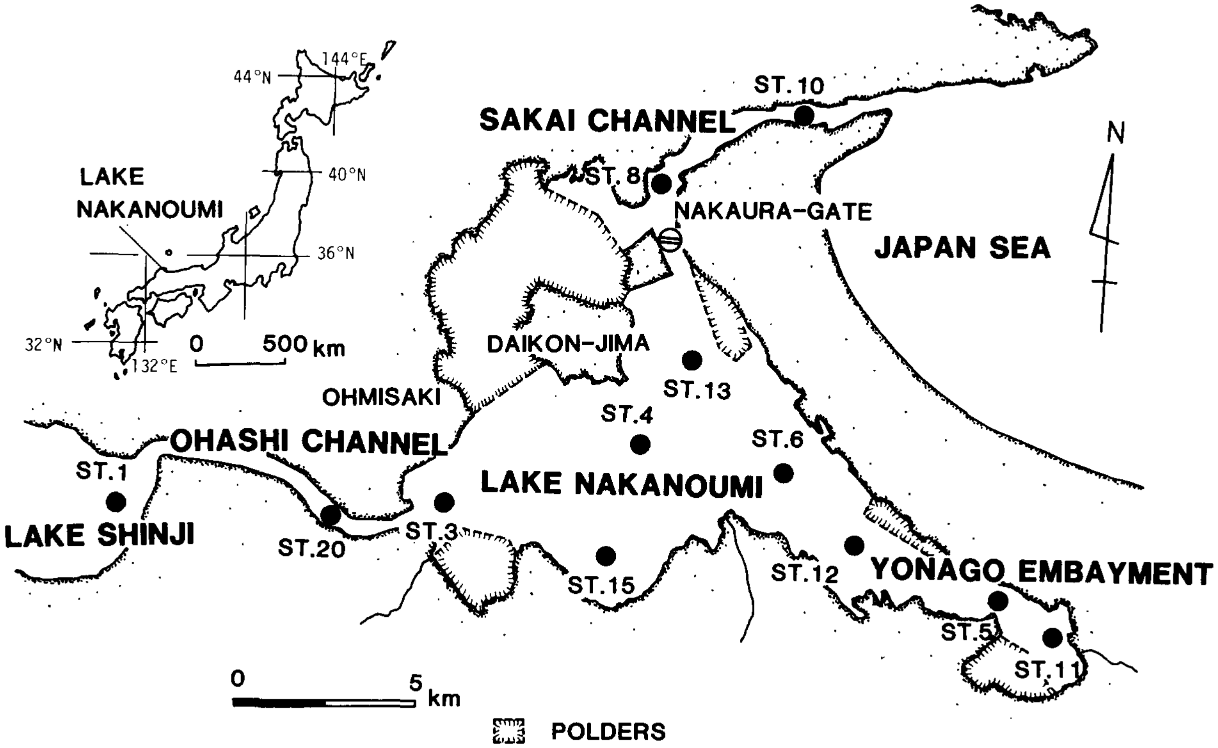

Fig. 1. Map of Lake Nakanoumi showing sampling stations (●).

Lake Nakanoumi and the freshening project

Lake Nakanoumi is located in the northwest part of the Japanese Archipelago (*ca* 35°30'N lat. and 133°10'E long.). The lake is connected with the Japan Sea via the Sakai channel which is approximately 0.3 km wide and 7.5 km long. Reclamation activities began in 1968 and the building of polder dykes has practically been completed by 1978. Prior to the reclamation activities, Lake Nakanoumi had a surface area of 97.5 km^2 and a total storage volume of 5.21×10^8 m^3 at the mean surface level of 0.2 m above the sea level. At present it has a surface area of 70.5 km^2 and a total storage volume of 3×10^8 m^3. The mean water depth is 5.4 m and the hypsographic curve shows about 80% of this study area is shallower than 7.0 m. The total inflowing water volume is 2.27×10^9 m^3 yr^{-1} and about 70% of it is contributed by the outflow from Lake Shinji. Thus norminal retention time (storage volume/inflowing water volume) is about 1.6 months. The outflow from Lake Shinji contains salinity of 5–15‰ (freshwater content of 60–90%), and the total freshwater discharge is to the extent of $1.6\text{–}2.1 \times 10^9$ m^3 yr^{-1}. Tides are predominantly semidiurnal with a mean range of about 0.3 m at the mouth of the Sakai Channel. Because of the narrow entrance, the tidal amplitude is reduced by nearly 60% in Lake Nakanoumi. Mean volume of the tidal prism is $1.1\text{–}1.5 \times 10^7$ m^3 and five times more water than is introduced by rivers during a tidal cycle (Ohtake *et al.*, unpublished). The Sakai Channel was dredged down to 10 m in 1969–1971 to increase the discharge capacity, and no barrier sill exists in the entrance to Lake Nakanoumi.

Lake Nakanoumi will be completely separated from the Japan Sea by the Nakaura-gate which was constructed across the Nakaura Channel during 1968–1974. The Nakaura-gate has ten drainage sluices and three ship locks near the center of the channel to allow the passage of vessels up to 5000 tons. During ebb tides the sluices are open to allow an unhindered flow of the lake water into the Sakai Channel, while during flood tides they are closed to block completely any return of the sea water back into the lake. It is predicted from scale model test and computer simulations that the surface salinity in Lake Nakanoumi will be reduced down to the extent of 0.4‰ within a year after the beginning of the freshening operation.

The physical hydrography of Lake Nakanoumi has been considerably changed by the reclamation activities including dyking, enlargement of channels and construction of the Nakaura-gate. Prior to the reclamation activities, the greater part of the river water inflowing from Lake Shinji flowed northeastwards between Ohmisaki and Daikonjima (see Fig. 1) toward the Sakai channel. However, after the Ohmisaki dyke was constructed between Ohmisaki and Daikonjima by March 1978, this northeastward flow is completely blocked and the brackish water from Lake Shinji flows past Sts. 3, 4 and 13 (Fig. 1) and arrives at the Nakaura-gate. At present the water exchange with the open sea is allowed only through the Nakaura-gate.

Methods

Sampling has been carried out at monthly intervals at 12 stations (Fig. 1) since January 1965. From the topographical viewpoint, this study area can be subdivided into five major parts: Lake Shinji, the Ohashi Channel, the main Nakanoumi, Yonago Embayment and the Sakai Channel. Since each of these areas has a somewhat different hydrographical structure and hydrochemistry, the 12 sampling stations were chosen to represent well the different conditions in this study area.

Surface and bottom water samples were taken by a nonmetallic Van Dorn water bottle having a capacity of 3 ℓ from 1 m below the surface and 1 m above the bottom, respectively. About 2 ℓ of the contents of the water bottle were put into a polyethylene sample-bottle and stored in ice chests. At the central part of Lake Nakanoumi (St. 4) samples were taken vertically at about 0.5 m intervals from the surface down to the bottom. Routine physical and chemical parameters were assessed after the Standard Methods (American Public Health Association 1975). After September 1975 the vertical salinity, temperature and oxygen profiles at the 12 stations were also measured *in situ* with the use of an inductive salinometer (Electronic Switchgear Type M.C.5, London) and a dissolved oxygen meter (Electric Instrument Model 1510, Surrey).

Phytoplankton species analysis was made for the surface water samples collected at Sts. 1, 3, 4, 8, 11 and 20. From the same water samples employed for routine chemical analyses, 200 mℓ subsamples were drawn off for phytoplankton analysis. The details on the enumeration and identification of phytoplankton species were mentioned previously (Ohtake *et al.* 1980a). Chlorophyll *a* determinations were according to Strickland & Parsons (1968).

In order to maintain efficiently the ever-increasing amount of data, the survey data were assembled into a computerized data-storage system (Nakane 1981). The system for data storage also made it possible to retrieve information for multiple data uses and to summarize these data into simple statistical parameters. The data storage and statistical analysis were carried out by FACOM M140, the Computer Center of Shimane University.

Results and discussion

Water temperature

Monthly mean surface and bottom water temperature measured during the period of 1974–1979 are shown in Fig. 2. Water temperature showed a regular seasonal cycle. The maximum surface water temperature (28–30 °C) was observed in August,

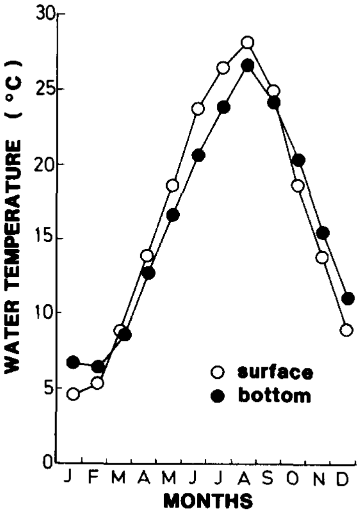

Fig. 2. Monthly surface and bottom water temperatures measured during the period of 1974–1979.

Table 1. Coefficients of variation (CV) in respect to a variety of temporal and spatial fluctuations of salinity.

Variation	Date	Station	Number of data	CV
Diurnal (hour-to-hour)	2–3 August 1979	St. 4 1 m	24[a]	0.04
		3 m	24	0.08
		6 m	24	0.02
Yearly (year-to-year)	1966–1979	St. 4 1 m	14[b]	0.24
		3 m	14	0.16
		6 m	14	0.13
Seasonal (month-to-month)	1974	St. 4 1 m	12	0.67
		6 m	12	0.56
	1976	St. 4 1 m	12	1.85
		6 m	12	0.50
	1978	St. 4 1 m	12	0.95
		6 m	12	0.25
Vertical (depth-to-depth)	8 January 1979	St. 4	13[c]	0.99
	9 May 1979	St. 4	13	1.20
	8 August 1979	St. 4	13	0.51
	3 October 1979	St. 4	13	0.78
Longitudinal (station-to-station)	8 January 1979	1 m	12	1.52
	9 May 1979	1 m	12	2.68
	8 August 1979	1 m	12	1.86
	3 October 1979	1 m	12	1.27

[a] Measured at 1-h intervals.
[b] Yearly means.
[c] Measured at 0.5-m depth intervals.

while the minimum (3–7 °C) in January. The surface temperature seldom fell below 4 °C even in winter. The annual temperature range was considerably wide, extending over approximately 20 °C in both surface and bottom waters. The vertical differences between surface and bottom waters were to the extent of 0–3 °C. In winter months the lagoon has inverse temperature differences because of the intrusion of warmer salt water into the bottom of Lake Nakanoumi. While thermal stratification is absent throughout the year, water density differences resulting from the vertical salinity gradient is of importance for the lake circulation. The details of density stratification will be presented separately.

Salinity

Table 1 summarizes the coefficients of variation (standard deviation divided by average) in respect to a variety of temporal and spatial fluctuations of salinity in this study area. Because of the relatively small size of the entrance channel in comparison with the lagoon's volume, the diurnal fluctuation of salinity in relation to tide is slight. On the other hand, longitudinal and vertical salinity gradients in the lagoon are large.

Figure 3 shows yearly mean salinities of surface and bottom waters at the nine stations along the transect starting from Lake Shinji to the Sakai Channel. Both the surface and bottom salinities remarkably decreased towards the interior of Lake Nakanoumi. Though omitted here, the mean values at the Yonago Embayment (Sts. 5, 11 and 12) were similar to those recorded in the main Nakanoumi (Sts. 4, 6 and 13). According to the Venice System 1958, this study area ranges from the oligohaline to the polyhaline zones over a relatively short distance (20 km). The salinity differences between St. 10 and St. 1 were about 20‰ in the surface layer and about 25‰ in the bottom water. On the whole, the vertical differences between surface and bottom waters tended to be smaller towards the interior of the lake. Since the freshwater discharged into Lake Nakanoumi tended to flow over the denser salt water intruding through the Sakai channel, the main Nakanoumi usually exhibited a vertical salinity profile with a remarkable halocline (Ohtake *et al.* 1980c).

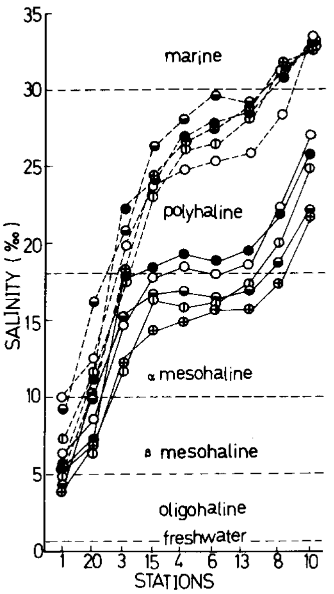

Fig. 3. Yearly mean salinities of surface (solid lines) and bottom (dashed lines) waters at the nine stations along the transect starting from Lake Shinji to the Sakai Channel, 1975–1979. (⦶) 1975; (⊕) 1976; (◒) 1977; (●) 1978; (○) 1979.

The detailed dynamics of mixing and circulation are beyond the scope of this paper, but it is worthwhile considering the flushing time in the lagoon. The flushing time (T) may be given by (Aston 1978)

$$T = \bar{f}\,\frac{V}{R} = \frac{\sigma - \bar{S}}{\sigma}\,\frac{V}{R}$$

where $\bar{f}$ is the averaged fraction of freshwater present in the lagoon, R is the rate of freshwater discharge into the lagoon, $\bar{S}$ is the mean salinity, V is the total volume of the lagoon and σ is the salinity of undiluted sea water. Using $\bar{S} = 19{,}1‰$, $R = 5.1 \times 10^6\ m^3\ day^{-1}$, $V = 3 \times 10^8\ m^3$ and $\sigma = 35‰$, the flushing time (T) was calculated to be 26.5 days at a mean freshwater discharge.

Figure 4 shows the changes occurring from month to month in the surface and bottom salinities in the main Nakanoumi during the 15-year period of 1966–1980. The amplitude of fluctuations in the surface salinity (S_s) were somewhat larger than those in the bottom salinity (S_b). The maximum values of surface ($S_{s\ max}$) and bottom ($S_{b\ max}$) salinities were 26.5‰ (August 1973) and 32.3‰ (May 1978), respectively. The minimum values were 5.3‰ (July 1972) in the surface water ($S_{s\ min}$) and 17.4‰ (March 1974) in the bottom water ($S_{b\ min}$). The vertical salinity differences between surface and bottom waters were in the range of 0.4 (October 1973) to 22.7‰ (July 1972), averaging 9.8‰.

The year-to-year fluctuation of the surface salinity in the main Nakanoumi was closely related to that of the annual precipitation (Table 2). The sig-

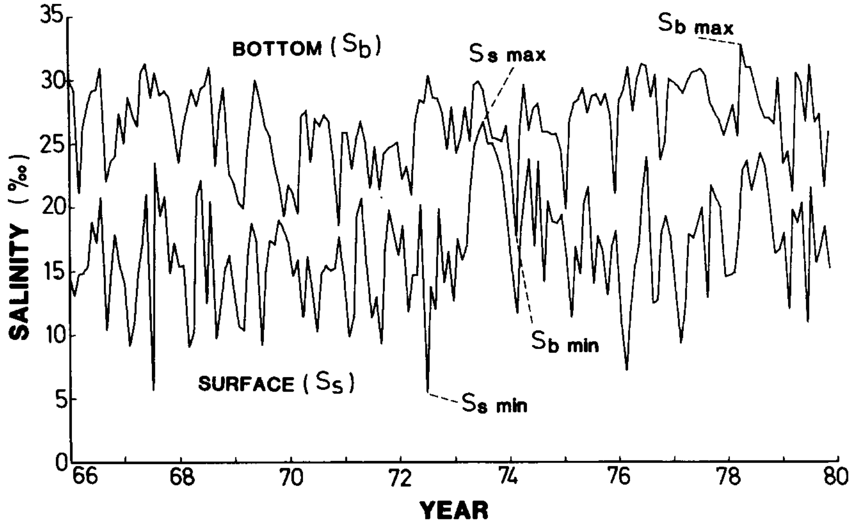

Fig. 4. Changes occurring from month to month in the surface and bottom salinities in the main Nakanoumi during the 15-year period of 1966–1980. The salinity values are means for Sts. 4, 6 and 13.

Table 2. Year-to-year fluctuation of the surface salinity in the main Nakanoumi and annual precipitation, 1966–1979.

Year	Yearly mean surface salinity[a] (‰)	Annual precipitation[b] (mm)
1966	15.6	1903
1967	15.6	1992
1968	14.8	1757
1969	15.1	1802
1970	14.6	1886
1971	13.2	2082
1972	14.6	2485
1973	21.2	979
1974	18.1	1675
1975	16.2	1839
1976	15.3	2034
1977	13.8	1764
1978	16.2	1517
1979	16.5	1799
$r = -0.769$; $P < 0.01$		

[a] Means for Sts. 4, 6 and 13.
[b] Measured at Matsue City.

nificant increase in the surface salinity observed in 1973 was caused by the extremely decreased precipitation. On a yearly basis, precipitation could be regarded as the major cause of surface salinity variation ($r = -0.769$, $p < 0.01$).

Table 3 shows the mean annual cycles of surface and bottom salinities in the main Nakanoumi for the period of 1974–1979 along with those of precipitation and tidal height measured at the mouth of the Sakai Channel. The freshening of the surface layer from February to April and the sharp rise in the surface salinity during the months from April to June were the features that recurred most regularly. The salinity minimum in early spring was connected with the increase in freshwater discharge caused by melting of snow, while the salinity maximum in summer was coupled with the temperature maximum (probably maximum evaporation) and large tidal height at the mouth of the Sakai channel. The multiple regression analysis (surface salinity versus precipitation and tidal height) showed a multiple correlation coefficient of 0.73 ($p < 0.01$). In the rainy season from late June to July, both surface and bottom salinities considerably decreased. It should be also mentioned that the decrease in surface salinity observed in September was associated with the large precipitation brought about by typhoons.

Dissolved oxygen

The surface waters were almost saturated with dissolved oxygen throughout a year (Table 4). During the warmer seasons from March to October, values of over 120% were often observed at the Yonago Embayment (St. 11). The over-saturation was the result of vigorous photosynthetic activities

Table 3. Mean annual cycles of surface and bottom salinities in the main Nakanoumi, precipitation and tidal height for the period of 1974–1979.

Months	Monthly mean salinity surface (Y) (‰)	bottom	Precipitation (X_1) (mm)	Tidal height (X_2)* (cm)
Jan.	15.7	25.4	147.9	3.4
Feb.	11.9	20.7	151.0	-2.8
Mar.	11.6	24.2	128.7	-4.8
Apr.	15.1	26.0	121.2	0.8
May	18.0	28.2	110.3	5.8
Jun.	19.4	28.5	170.2	18.2
Jul.	13.3	25.9	269.9	26.8
Aug.	17.7	26.9	154.1	31.4
Sep.	15.1	26.3	207.9	28.6
Oct.	17.8	26.5	132.7	22.0
Nov.	17.5	25.3	141.1	11.0
Dec.	16.2	22.6	127.9	5.0

Regression equation: $Y = -0.042\,X_1 + 16.15\,X_2 + 20.4$ $R = 0.73$; $F = 4.30$.
* Measured at the mouth of the Sakai Channel.

Table 4. Mean annual cycle of dissolved oxygen content (%) in surface and bottom waters for the period of 1974–1979.

Months	Oxygen saturation (%)			
	St. 1	St. 4	St. 11	St. 10
Surface waters				
Jan.	84.4	85.3	77.9	86.7
Feb.	94.6	91.7	94.6	114.5
Mar.	95.0	103.5	121.8	102.6
Apr.	103.4	118.2	129.8	110.0
May	89.5	104.3	98.9	93.8
Jun.	84.5	106.9	115.7	100.3
Jul.	82.1	108.6	137.8	98.9
Aug.	61.2	109.0	162.3	117.0
Sep.	81.0	106.0	122.0	95.0
Oct.	93.6	117.2	132.8	105.8
Nov.	99.0	99.6	114.0	99.0
Dec.	95.8	94.5	103.8	97.3
Bottom waters				
Jan.	84.2	67.8	75.2	81.6
Feb.	93.3	59.4	85.0	105.0
Mar.	94.6	65.3	92.0	96.3
Apr.	99.6	42.0	66.8	100.7
May	76.3	27.9	47.0	93.3
Jun.	75.2	25.2	47.6	91.8
Jul.	63.1	29.1	21.9	93.6
Aug.	50.5	9.5	21.0	97.0
Sep.	63.5	13.6	10.0	87.0
Oct.	78.8	23.2	50.4	90.2
Nov.	89.0	59.8	79.2	87.6
Dec.	92.4	68.0	74.3	94.1

* Measurements were performed between 0900 and 1200 JST.

during the period. Actually, sporadic blooms of dinoflagellates such as *Prorocentrum minimum* and *Gymnodinium* spp. have often been observed in early spring and autumn (Ohtake *et al.* 1980a).

The oxygen content of the bottom waters at Sts. 4 and 11 showed a distinct seasonal cycle with remarkably low values in summer. The summer oxygen content of bottom waters often fell below 10% (less than 1 mg O_2 ℓ^{-1}) despite of the vigorous oxygen production in the surface waters. This suggests that the vertical transport of dissolved oxygen was strongly inhibited by the stable halocline which usually developed at a depth of 3–4 m (Ohtake *et al.* 1980c). On the other hand, the oxygen content of the bottom water of the Sakai Channel (St. 10) never fell below 80% even in summer.

Reflecting the water quality deterioration probably because of the lack of a proper public sewer system, the summer oxygen content of the bottom water at the central part of Lake Nakanoumi (St. 4) has substantially decreased during the past 15 years (Fig. 5). However, after the enlargement of the Nakaura Channel and the construction of the Nakaura-gate by 1974, sea water containing high dissolved oxygen could enter directly into the bottom of the main Nakanoumi, and the bottom oxygen content somewhat increased up to 2 mg O_2 ℓ^{-1}.

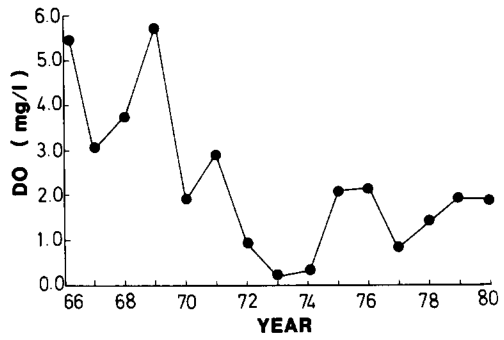

Fig. 5. The summer-mean (July to September) concentrations of dissolved oxygen of the bottom water at the central part of Lake Nakanoumi (St. 4), 1966–1980.

Inorganic nutrients

The comparison of 12 stations in respect to T-P and PO_4-P concentrations (Fig. 6) reveals that high values were found at the Yonago Embayment (Sts. 5, 11 and 12). A city of approx. 110 000 inhabitants discharged its waste waters into this small water area having a sluggish water movement. It appears that the high T-P concentrations resulted from both municipal waste waters and poor circulation. To the contrary, low concentrations were found at the Sakai Channel (Sts. 8 and 10), particularly in the bottom waters, where pollutants could be easily washed away via tidal movements. Though omitted here, T-N concentrations were also high in the Yonago Embayment and decreased along the transect from Lake Shinji to the Sakai Channel. The local high nutrient concentrations were accompanied by high primary productivity (Date 1978). The net primary productivity measured at the Yonago Embayment during the summer of 1975 was to the extent of 1.30 g C m^{-2} day^{-1} (August 1975) to 2.22 g C m^{-2} day^{-1} (June 1975).

For the seasonal cycles, T-P concentration

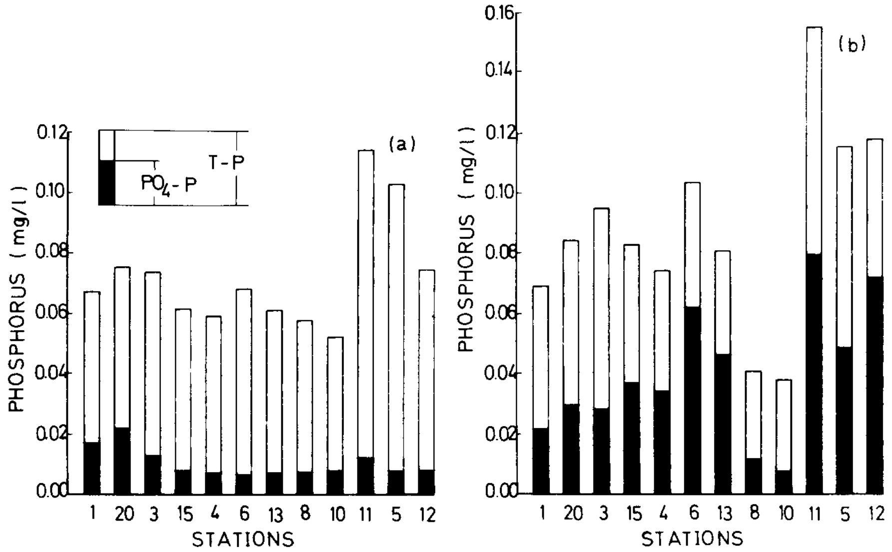

Fig. 6. The comparison of 12 stations in respect to T-P and PO_4-P concentrations. T-P and PO_4-P concentrations are the station-means of surface (a) and bottom (b) waters sampled during the period of 1976–1979.

showed a distinct feature with quite high values in summer (Fig. 7). The marked increase in T-P concentration of the bottom water in summer was closely related to the release of PO_4-P from bottom sediments (Ohtake *et al.* 1982). Ohtake *et al.* (1982) estimated the release rate of PO_4-P in summer as 10–20 mgP m^{-2} day^{-1} from the actual field data on the vertical phosphorus profiles in Lake Nakanoumi. Barnes (1980) pointed out that lagoons are frequently nutrient-rich, both as a result of the input of nutrients by rivers and through the effectiveness of recycling between sediment and water mass. It is

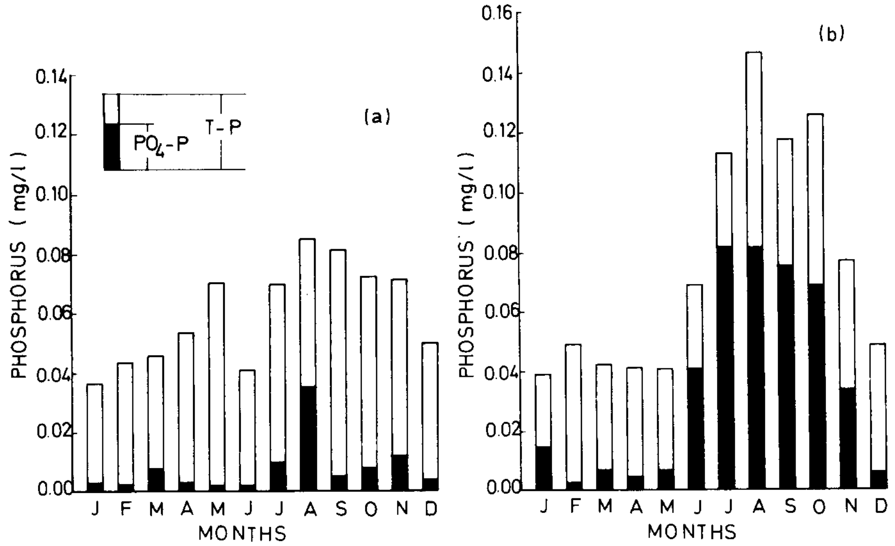

Fig. 7. Mean annual cycle of T-P and PO_4-P in the main Nakanoumi (St. 4), 1976–1979, T-P and PO_4-P concentrations are monthly mean values of surface (a) and bottom (b) waters sampled during the period of 1976–1979.

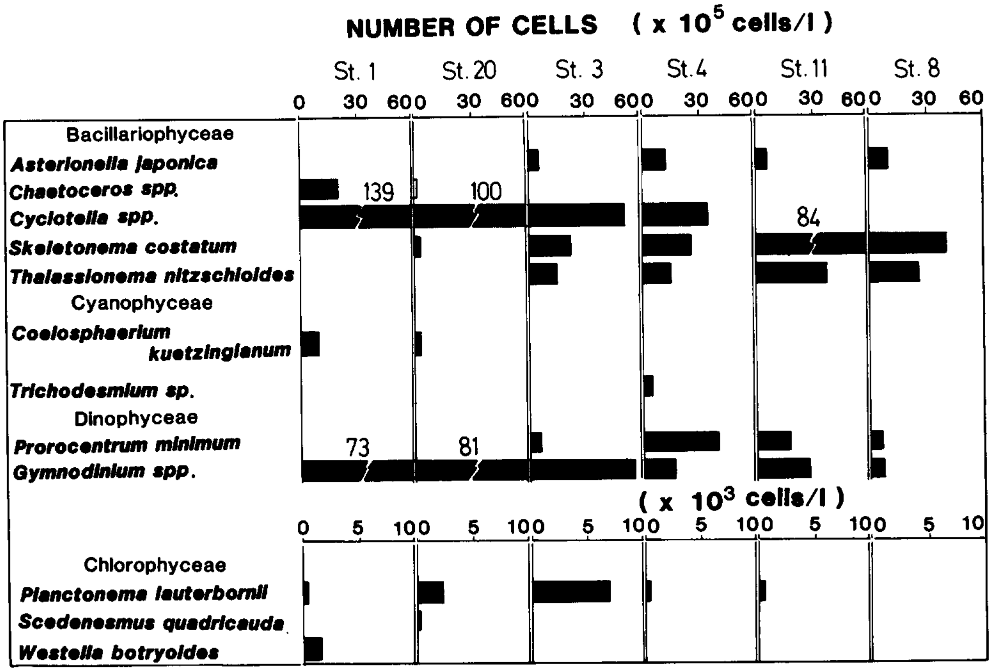

Fig. 8. Dominant species of phytoplankton communities in Lake Nakanoumi. Cell numbers are the station-means in 1979.

likely that the nutrient recycling between sediment and water mass can produce obvious effects on this shallow lagoonal environment where the volume of water per unit area is considerably small.

Phytoplankton species

Details of the phytoplankton distribution during the period of 1974–1978 have been given in previous papers (Ohtake *et al.* 1980a, b). In 1979 the total number of phytoplankton species comprised 52 species: 34 Bacillariophyceae, 6 Chlorophyceae, 6 Cyanophyceae, 5 Dinophyceae and 1 Cryptophyceae. The comparison of stations in respect to dominant species is shown in Fig. 8. The six stations are arranged from St. 1 to St. 8 in increasing order of the yearly mean salinity (see Fig. 3). On the whole, the species compositions were similar to those recorded during the period of 1974–1978 (Ohtake *et al.* 1980a, b). The dominant species are the marine and brackish diatoms *Skeletonema costatum, Thalassionema nitzschioides* and *Astrionella japonica,* the freshwater species of *Cyclotella* and the flagellates such as *Prorocentrum minimum* and *Gymnodinium* spp. Particularly *Gymnodinium* spp. was abundant at all stations in 1979. Ohtake *et al.* (1980a) pointed out that the phytoplankton assemblages of Lake Nakanoumi had salient regional features which were closely connected with the surface salinity gradients. In 1979 the occurrence of green algal species such as *Planctonema lauterbornii* and *Westella botryoides* were almost restricted to the low-salinity region from St. 1 to St. 3. Although *Cyclotella* spp. were abundant in the low-salinity region, the diatoms *Skeletonema costatum* and *Thalassionema nitzschioides* were the most abundant species at the Sakai Channel where the surface salinity was highest among the six stations. The percentage of diatoms in the total cell numbers observed during the period of 1977–1979 increased with increasing salinity from 39.5% at St. 1 to 77.5% at St. 8. These results were consistent with those obtained in the previous works (Ohtake *et al.,* 1980a, b). It should be mentioned that sporadic red tides of dinoflagellates often occurred throughout the lake in 1979.

The phytoplankton species analyses were carried out only for the surface water samples collected from 1 m below the surface, and it is worthwhile describing the vertical profiles of chlorophyll *a* in Lake Nakanoumi. Figure 9 shows the annual cycle of chlorophyll *a* concentration at the central part of

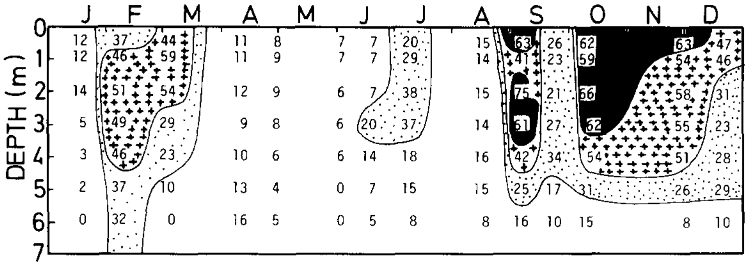

Fig. 9. The depth–time distribution of chlorophyll *a* at the central part of Lake Nakanoumi (St. 4) in 1979.

Lake Nakanoumi (St. 4) in 1979. High concentrations were found in the 0–4 m layer (11–19‰). As mentioned before, a stable halocline developed at a depth of 3–4 m and separated the well oxygenated upper layer from a lower layer poor in oxygen. The halocline appears to have an effect upon the vertical distribution of phytoplankton due to impeding of the vertical mixing in this shallow lagoon.

As regards the seasonal cycle, the two peaks are discernible in early spring (7–10 °C) and late autumn (15–20 °C). The large concentrations in February and March were due almost entirely to populations of the diatom *Skeletonema costatum* and the dinoflagellate *Prorocentrum minimum.* The populations of the diatom species *Asterionella japonica* and *Ditylum* sp. were largely responsible for the peak in late autumn.

Comparative analyses

Figure 10 shows a comparison of the coefficients of spatial and temporal variations of 14 common water parameters in Lake Nakanoumi. The coefficients of variation between sampling stations ($CV_{\text{station-to-station}}$) were calculated from the station-mean values for the period of 1974–1979. On the other hand, the coefficients of variation with respect to seasonal fluctuations ($CV_{\text{month-to-month}}$) were obtained from the monthly means for the period of 1974–1979. That is, the values of $CV_{\text{month-to-month}}$ were based on the mean annual cycles of water parameters during the period.

As can be seen in Fig. 10, pH value had minimum variabilities both seasonally and regionally. Abbott & Dawson (1971) indicated that estuarine pH is maintained as a conservative property except in unusual cases involving highly acidic bog drainage or discharge of strongly alkaline or acidic wastes. It appears that pH is behaving conservatively also in this lagoonal environment. Salinity considerably varied regionally, as mentioned earlier (Table 1); larger variabilities were found with respect to inorganic nutrients such as PO_4-P, NO_3-N and NH_4-N. Chlorophyll *a* also showed a large spatial variability.

For the seasonal variabilities, the common water parameters except for pH showed larger variabilities in comparison with that of salinity which could be regarded as a conservative parameter. This suggests that these parameters are seasonally subjected to complex factors other than physical mixing. As shown in Fig. 2 water temperature considerably fluctuated throughout a year. However, NO_3-N and PO_4-P showed the largest variabilities, which were much larger than that of water temperature. By contrast, total nitrogen showed relatively low seasonal variability. Despite the distinct changes in nitrogeneous fractions, T-N concentration tended to be maintained as a conservative parameter.

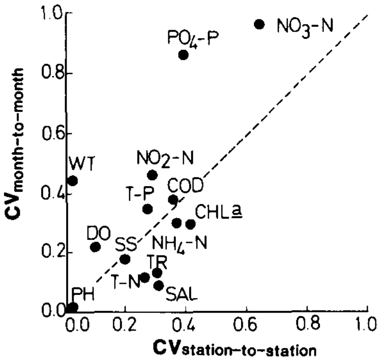

Fig. 10. A comparison of the coefficients of spatial and temporal variations of 14 common water parameters in Lake Nakanoumi. WT = water temperature, SS = suspended matter, TR = turbidity, SAL = salinity, CHL *a* = chlorophyll *a*.

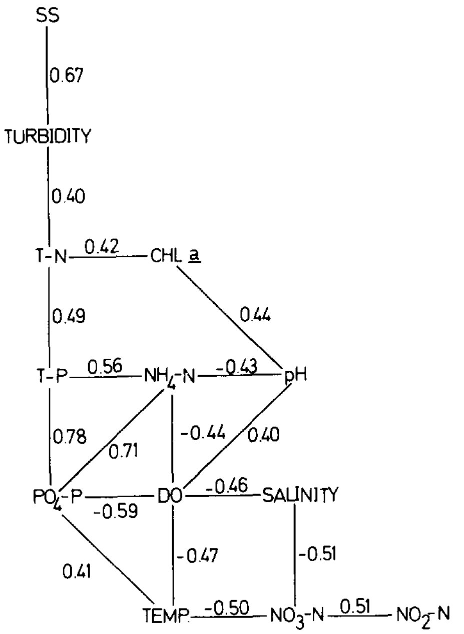

Fig. 11. Cross correlation coefficients between the 14 common water parameters. For convenience of illustration, the relations having the correlation coefficients larger than 0.4 or less than -0.4 was presented.

The cross correlation coefficients between the 14 common parameters were calculated to show the interrelationships between them (Fig. 11). Because of the large number of data (more than 2 000), cross correlation coefficients higher than 0.05 (or less than -0.05) were statistically significant at the 99% confidence level. However, for convenience of illustration, only those relations with correlation coefficients larger than 0.4 or less than -0.4 are given in Fig. 11. Though many of the relationships shown in Fig. 11 are indirect ones and the correlation coefficients provide only a pilot information on relationships between individual parameters, they could be used for a guide to the construction of a model for this brackish water environment.

The highest correlation coefficients were for T-P and PO_4-P (0.78), PO_4-P and NH_4-N (0.71), and turbidity and suspended matter (0.67), as expected. The negative correlations in DO concentration with water temperature and also with salinity can be interpreted by the fact that DO concentration of bottom waters having higher salinity decreased with increasing water temperature (see Table 4). Significant negative correlations were also observed between PO_4-P and DO, and NH_4-N and DO. These results reflect the fact that the release of PO_4-P and NH_4N from lake sediments as considerably enhanced by low DO concentration, as reported previously (Ohtake *et al.* 1982). Hence it appears that the relationship between PO_4-P and NH_4-N is an indirect one which is dependent on a third parameter DO. Since NO_3-N was relatively abundant in the well-oxidized upper layer above the halocline in winter, the negative correlations were found between NO_3-N and water temperature, and NO_3-N and salinity. The high correlation between chlorophyll *a* and pH can be interpreted by algal photosynthesis activity. Chlorophyll *a* was also closely related to T-N concentration, but not to T-P concentration ($r = 0.13$). Many investigators have characterized coastal marine and estuarine waters as nitrogen limited for algal growth (Stumm & Stumm-Zollinger 1972). On the whole, nitrogen availability appears to be a major regulating factor for phytoplankton growth in Lake Nakanoumi.

Conclusions

The salient features of the lagoonal environment of Lake Nakanoumi are summarized as follows:

1. The annual range of water temperature was considerably wide, extending over approximately 20 °C in both the surface and bottom waters. The vertical differences between surface and bottom waters were to the extent of 0-3 °C. The inverse vertical temperature differences were usually observed during the winter months.
2. Both the surface and bottom salinities remarkably decreased towards the interior of Lake Nakanoumi. The main Nakanoumi usually exhibited a vertical salinity profile with a remarkable halocline. On a yearly basis, precipitation could be regarded as the major cause of surface salinity variation. Regular seasonal changes in the surface salinity were observed; the surface salinity was minimum in early spring and maximum in summer.
3. The surface waters were almost saturated with dissolved oxygen throughout a year. On the other hand, the oxygen content of the bottom waters in the main Nakanoumi and the Yonago Embayment showed a distinct seasonal cycle

with remarkably low values in summer. It appears that the vertical transport of dissolved oxygen was strongly inhibited by the stable halocline.

4. The concentrations of T-P and T-N were high in the Yonago Embayment. T-P concentration in the main Nakanoumi had a distinct seasonal cycle with quite high values during the summer months, which was tightly connected with the release of PO_4-P from lake sediments.
5. The phytoplankton communities of Lake Nakanoumi had salient areal features which were closely related with the surface salinity. The dominant species are the marine and brackish diatoms *Skeletonema costatum, Thalassionema nitzschioides* and *Asterionella japonica,* the freshwater species of *Cyclotella,* and flagellates such as *Prorocentrum minimum* and *Gymnodinium* spp.

No quantitative studies have been made on the dynamics of mixing and circulation and no unequivocally accepted picture exists yet in regard to water exchange patterns between Lake Nakanoumi and the Japan Sea. Aston (1978) pointed out that the erratic fluctuations in river run-off and the rhythmic tidal cycles give rise to major difficulties in the sampling of estuaries, the modelling of estuarine processes and the comparison of individual estuaries with each other. Statistical approaches using more than 200 000 routine data could reduce the difficulties and the present data would be useful to the understanding of the complex and unique environment of shallow lagoons.

Little is known about the effect of artificial freshening on a lagoonal environment, and as yet it is impossible to predict precisely what will happen after the completion of the project. It is very important that efforts be made to accumulate further survey data. Meaningful information on environmental impact assessment could be obtained from documenting the changes in the lagoonal environment with the progress of desalinization of lake water.

Acknowledgments

This work was supported by the Grant in Aid of Scientific Research from the Ministry of Education, Culture and Sciences of Japan. We are indebted to the Office of Nakanoumi Reclamation Project, the Ministry of Agriculture and Forestry of Japan for the assistance in sample collection.

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Received 26 October 1981; in revised form 3 March 1982.