Nitrogen Metabolism in the Brackish Lake Nakanoumi. IV.
—Seasonal Variation of Nitrate Nitrogen—

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Abstract

The seasonal variation of nitrate in the upper layer in the brackish Lake Nakanoumi has been investigated by the analysis of the data collected monthly during the period of 1976-1986. Upward trends in nitrate concentration were found in the colder season (January to March), and also in the rainy season (July). In contrast to nitrate, chlorinity decreased at the same time.

A significant negative correlation between nitrate concentration and chlorinity in the surface water in Lake Nakanoumi was found in January, February, March and July. In addition, from the analysis of the correlation between the increment of nitrate concentration in the surface water and cumulative rainfall, it was concluded that the accumulation of nitrate in the upper layer is mainly caused by discharge from the rivers into the lake through rainfall and melted snow.

Key words : nitrate, seasonal variation, rainfall, brackish lake

1. Introduction

The major nitrogenous nutrients in aquatic environments are nitrate and ammonium. The behavior of the nitrate, as well as ammonium, is important in the nitrogen metabolism in natural waters.

We reported that nitrate and especially nitrite, which are derived from oxidation of ammonium by nitrifying bacteria, accumulate in the bottom layer in Lake Nakanoumi from August to September (SEIKE et al., 1986b). Similar accumulation of nitrate in the hypolimnion during the stratification period has also been reported for several lakes (TAKAHASHI et al., 1982 ; YOSHIOKA and SAISO, 1985 ; TEZUKA, 1984, 1985b).

On the other hand, TEZUKA (1985a) reported that the nitrate plus nitrite level in Lake Biwa during the warmer season was controlled by the amount of rainfall. TERAI (1988) also reported a significant correlation between the nitrate concentration of Lake Fukami-ike in mid-March and the amount of rainfall during February to March. As pointed out by TEZUKA (1985a), however, more long-term observations would be needed to establish such a relationship.

The present study was undertaken to clarify a seasonal variation of nitrate in the upper layer in the brackish Lake Nakanoumi by the analysis of the monthly data collected at 12 stations during the period of 1976-1986. The results clearly showed that the nitrate concentration in the upper layer of this lake increased both in winter and in July. The mechanism for such a seasonal variation of nitrate concentration is discussed.

2. Materials and methods

2-1. Study area

Lake Nakanoumi is located in the northwestern part of the Japanese Archipelago (ca. Lat. 35° 30' N and Long. 133° 10' E). The lake is connected with Lake Shinji via the Ohashi Channel, which is 7.5 km long (Fig. 1). It has
a surface area of 72 km² and a total storage volume of $3 \times 10^8$ m³. The mean water depth is 5.4 m and about 80% of this study area is shallower than 7.0 m. The total inflowing water volume is $2.27 \times 10^9$ m³ yr⁻¹, in which the inflow from Ohashi Channel comprises 70% of the total (OHTAKE et al., 1982). The lake is also connected with Japan Sea via the Sakai Channel, which is approximately 0.3 km wide and 7.5 km long.

2-2. Sampling

Observation was carried out at monthly intervals at 12 stations in Lake Nakanoumi and the six rivers discharging into the lake (Fig. 1). The period of observation was 11 years (1976 to 1986), except for six years at Sta. 7 (1981 to 1986). Sampling date of the six rivers differed from that of Lake Nakanoumi.

Surface, middle and bottom water samples were collected with a Van Dorn type sampler of 3 I capacity from 1 m below the surface, the middle of the water column and 1 m above the bottom, respectively. At the central part of Lake Nakanoumi (Sta. 4) samples were taken vertically at about 1 m intervals from the surface down to the bottom.

2-3. Chemical analysis

Ammonium was measured by the indophenol method (SAGI, 1966). Nitrite and nitrate were measured by the method of BENDSCHNEIDER and ROBINSON (1952) and WOOD et al. (1967), respectively. Chlorinity was measured by the MOHR-KNUDSEN method.

3. Results

3-1. Inorganic nitrogen and chlorinity in Lake Nakanoumi

3-1-1. Mean seasonal variations of inorganic nitrogen and chlorinity

Mean monthly variations of vertical distribution (1981–1986) of ammonium, nitrite and nitrate at the central part of Lake Nakanoumi (Sta. 4) are summarized in Figure 2. Mean monthly variations (1981–1986) of chlorinity at the surface, the middle and the bottom at Sta. 4 are shown in Figure 3.

Ammonium concentrations were generally low in the euphotic layer (0–3 m), while the concentrations were very high near the bottom. The high concentrations (exceeding 30 μgN⁻¹...
Seasonal Variation of Nitrate in Lake Nakanoumi

1-1) of nitrite were observed in the hypolimnion from August to September. The increase of nitrite concentration was derived from oxidation of ammonium by nitrifying bacteria (SEIKE et al., 1986b). Higher nitrate values were observed in the whole water column from January to April and in the upper layer in July.

The highest nitrate value, 150 μgN•l⁻¹, was obtained in February at 0 m layer. In contrast with ammonium, these values were much higher in the upper layer than in the bottom layer.

On the other hand, remarkable decreases of chlorinity were observed at the surface and middle layer in January to March, and also in July (Fig. 3). The extent of the chlorinity variation was much higher at the upper layer than at the bottom layer.

Mean monthly variations (1976-1986) of nitrate concentration (Fig. 4a) and chlorinity (Fig. 4b) of the surface water at several other stations are shown in Figure 4. An upward trend in the nitrate concentration in winter (January to March) was found at all stations. At stations 20, 3, and 5, a similar upward trend was also found in July. On the other hand, chlorinity decreased at all stations in winter and July.

3-1-2. Horizontal distributions of nitrate concentration and chlorinity

Mean distributional patterns of nitrate and chlorinity in the surface water from the center of the Ohashi Channel to the mouth of the Sakai Channel (Stas. 20, 3, 4, 13, 8 and 10 : see Fig. 1), and from the Yonago Embayment to the mouth of the Sakai Channel (Stas. 11, 5, 12, 6, 13, 8 and 10 : see Fig. 1) are shown in Figure 5. The data in February, May, July and October are described here.

The nitrate concentrations remarkably de-
Fig. 4. Mean monthly variation of nitrate concentration (a) and chlorinity (b) in the surface water of Lake Nakanoumi in 1976-1986. ○, Sta. 20; △, Sta. 3; □, Sta. 13; ×, Sta. 10; ●, Sta. 5.

Fig. 5. Mean distributional pattern of nitrate concentration (a) and chlorinity (b) in the surface water from the center of the Ohashi Channel (Sta. 20) to the mouth of the Sakai Channel (Sta. 10) and from the Yonago Embayment (Sta. 11) to the mouth of the Sakai Channel (Sta. 10) in 1976-1986. ○, February; □, May; ○, July; ●, October.
Seasonal Variation of Nitrate in Lake Nakanoumi

3-2. Relationship between rainfall and chlorinity in Lake Nakanoumi

Correlations between cumulative rainfalls during the preceding 2–40 days (data of the sampling day itself were excluded) and decrements of chlorinity in the surface water against the previous month were examined at the representative stations (Stas. 20, 4, 8 and 5), and the results are shown in Figure 6a-c. In Figure 6, the ordinate denotes the correlation coefficient between cumulative rainfall and decrement of chlorinity in the surface water, and the abscissa denotes the cumulative days of rainfall.

In all seasons (Fig. 6a), the correlation coefficients gradually increased with cumulative days up to 25 days. The highest values at the central part of the lake (Sta. 4), Yonago Embayment (Sta. 5), and Sakai Channel (Sta. 8) were −0.72, −0.75 and −0.79, respectively, while the highest value (−0.50) at the Ohashi Channel (Sta. 20) was lower than that of the other stations. In January to March (Fig. 6b), the highest values at Stas. 4, 5 and 8 were −0.66, −0.56 and −0.51, respectively, whereas no significant correlation was obtained at Sta. 20. In July (Fig. 6c), the significant correlations (−0.92, −0.86, −0.95 and −0.81) were obtained at the above four stations.

3-3. Mean monthly nitrate concentrations of rivers discharging into Lake Nakanoumi

Mean monthly nitrate concentrations of the six rivers (Iu R., Iinashi R., Yoshida R., Hakuta R., Shinkamo R., Kyukamo R. in Fig. 1) discharging into Lake Nakanoumi are shown in Table 1.

The maximum values of 420 (Iu R.), 411 (Iinashi R.), 477 (Yoshida R.), 545 (Hakuta R.), 1,061 (Shinkamo R.), and 741 μgN·l⁻¹ (Kyukamo R.), were observed from December to February. On the other hand, the minimum values (except for Iu river) were observed in August. Thus nitrate concentrations of these rivers increased in winter, and decreased in

Fig. 6. Relationships between correlation coefficient and cumulative days of rainfall in 1976–1986. Vertical-axis : Correlation coefficient between cumulative rainfall and decrement of chlorinity in the surface water. Horizontal-axis : Cumulative days of rainfall. (a), all season ; (b), Jan.–Mar. ; (c), July ; O, Sta. 20 ; ⊙, Sta. 4 ; ◎, Sta. 8 ; ●, Sta. 5.
The nitrate concentrations of Shinkamo R. and Kyukamo R. flowing through the urban area of Yonago-shi to Yonago Embayment, were much higher than in the other rivers throughout all seasons. The nitrate concentrations of these six rivers were considerably high compared with that of lake water of Nakanoumi (cf. Figs. 4a and 5a).

### 3-4. Relationships between nitrate concentration and chlorinity in Lake Nakanoumi

The correlations between nitrate concentration and chlorinity in the surface water of Group-A and Group-B were examined, using the monthly mean values in January, February, March and July during the period of 1976-1986 (Fig. 7). Group-A values are along the line from the center of Ohashi Channel (Sta. 20) to the mouth of the Sakai Channel (Sta. 10), and Group-B values are along the line from the Yonago Embayment (Sta. 11) to the Nakaura Gate (Sta. 13).

As for Group-A, the highest values of the nitrate concentrations were found at the center of the Ohashi Channel where loading of domestic waste of Matsue-shi exerts an influence, and the values decreased toward the mouth of the Sakai Channel. The significant correlation coefficients were $-0.98$ (January), $-0.96$ (February), $-0.92$ (March) and $-0.80$ (July), respectively.

On the other hand, as for Group-B, the highest values were found at the Yonago Embayment (Stas. 11 and 5) where there are effects of discharges from Shinkamo R. and Kyukamo R., which have a high nitrate concentration (cf. Table 1), and the values also decreased toward the Sakai Channel. In January and February, significant correlations were noted between the nitrate concentration and chlorinity in the surface water, but none were observed in March and July.

Next, the correlations between the nitrate concentration and chlorinity in the surface water in Group-A were examined in every monthly data. The results obtained with the data collected in January, February, March and July during the period of 1976-1986 are shown in Table 2. In winter (January to March), mostly clear correlations were obtained, but no significant correlations were found in January and February 1979 when there was abnormally warm weather. On the other hand, in July, the significant correlations in Group-A (except for Stas. 8 and 10) were found in 1979, 1980, 1981 and 1986. The correlation coefficients were $-0.99$, $-0.93$, $-0.83$ and $-0.88$, respectively. But, no correlations were observed in July of 1976, 1977, 1978, 1982, 1983, 1984 and 1985.

### 4. Discussion

#### 4-1. Main factor in increase of nitrate concentration

It is well known that a causal factor for the increase of nitrate concentration in a lake water is the oxidation of ammonium by nitrifying bacteria (Takahashi et al., 1982; Yoshikawa and Sajo, 1985; Tezuka, 1985b). We have already reported a high accumulation of nitrate and especially nitrite, from August to September in the hypolimnion at the central part of Lake Nakanoumi, due to biological nitrification (Seike et al., 1986b).
In this study, however, it was found that the nitrate concentration in winter was high compared with that of the other seasons, and also the concentration in epilimnion was higher than that in hypolimnion of Lake Nakanoumi in January, February, March and July (Fig. 2). The present results cannot be explained by the nitrification, because the activity of nitrifying bacteria is regulated by water temperature (PAINTER, 1970), and the oxidizing bacteria of ammonium and nitrite are inhibited by light (YOSHIKA and SAJO, 1984, 1985).

As shown in Figures 5a and 7, the highest concentration of nitrate at the stations examined in this study was observed at Ohashi Channel where there is strong influence from loading of domestic waste of Matsue-shi and at the Yonago Embayment where there is inflow from Shinkamo R. and Kyukamo R. containing a high level of nitrate concentration (cf. Table 2).

Table 2. Correlation coefficients between nitrate concentration and chlorinity in the surface water from the center of the Ohashi Channel to the mouth of the Sakai Channel (Stas. 20, 3, 15, 4, 13, 7, 8, 10) in January, February, March and July 1976-1986. The data in July exclude Stas. 8 and 10.

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<tr>
<td>Jan.</td>
<td>-0.98</td>
<td>-0.97</td>
<td>-0.86</td>
<td>-</td>
<td>-0.88</td>
<td>-0.99</td>
<td>-0.99</td>
<td>-0.63</td>
<td>-0.93</td>
<td>-0.45</td>
<td>-0.97</td>
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<td>Feb.</td>
<td>-0.79</td>
<td>-0.99</td>
<td>-0.99</td>
<td>-</td>
<td>-0.97</td>
<td>-0.97</td>
<td>-0.62</td>
<td>-0.80</td>
<td>-0.88</td>
<td>-0.69</td>
<td>-0.99</td>
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<tr>
<td>Mar.</td>
<td>-0.80</td>
<td>-0.96</td>
<td>-0.91</td>
<td>-0.70</td>
<td>-0.99</td>
<td>-0.97</td>
<td>-0.94</td>
<td>-0.68</td>
<td>-0.95</td>
<td>-0.68</td>
<td>-0.98</td>
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<td>Jul.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.99</td>
<td>-0.93</td>
<td>-0.83</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-0.88</td>
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Moreover, significant negative correlations were found between nitrate concentration and chlorinity in the surface water (Fig. 7 and Table 2). These results suggest that the accumulated nitrate was not due to internal production such as nitrification, but to supply from some source of external origin.

In addition, direct relationships between cumulative rainfall and increment of nitrate concentration at the four stations (Stas. 20, 3, 11 and 5) near Matsue-shi and Yonago-shi could be examined. Figure 8 shows the result of such an examination using the data in the rainy season, July from 1976 to 1986. Clear correlations between rainfall during the preceding 7-11 days and the increment of nitrate concentration in the lake water were found. The maximum correlation coefficients were 0.97 (Sta. 20), 0.98 (Sta. 3), 0.94 (Sta. 11) and 0.93 (Sta. 5), respectively.

From the above results, it is concluded that the increase of nitrate concentration in the surface water of Lake Nakanoumi is mainly caused by discharge from the rivers into the lake through rainfall and melted snow. It has also been reported that the increases of nitrate in Lake Biwa (Tezuka, 1985a) and Lake Fukushima (Terai, 1988) originated from the supply of nitrate through rainfall and runoff.

### 4-2. Seasonal appearance and disappearance of nitrate

Though the amount of nitrate supplied from the rivers in summer (July) seems to be higher than that in winter (cf. Tables 1 and 3), the nitrate concentration of lake water in summer was considerably lower than that in winter (Figs. 2 and 4a). The reason for this phenomenon is discussed here from the viewpoint of the seasonal variation of nitrate uptake by phytoplankton.

As shown in Figure 6c, the correlation coefficients in July between the decrement of chlorinity in the surface water and cumulative rainfalls were gradually enhanced with the cumulative days of rainfall up to 25 days. On the other hand, the increment of nitrate concentration in July (Fig. 8) was influenced most strongly by rainfalls during the preceding 7-11 days. In addition, high nitrate concentrations were observed in 1979, 1980, 1981 and 1986, when there was a great deal of rainfall during the preceding 7 days; however, when we had a great deal of rainfall during the preceding 25 days (1977, 1984 and 1985), the nitrate concentrations were very low (Tables 4 and 5). Moreover, significant negative correlations (1979, 1980, 1981 and 1986) between nitrate concentration and chlorinity were observed in July of 1979, 1980, 1981 and 1986, but no such correlations were noted in 1977, 1984 and 1985 (Table 2). These results suggest that the nitrate supplied into the lake through rainfall more than 7-11 days ago was influenced not only by diffusion but also by phytoplankton uptake.

In general, nitrogen uptake by natural phytoplankton is regulated by the environmental variables, such as water temperature (Toetz et al., 1977; Seike et al., 1986a) and irradiance (Eppley et al., 1979; Mitamura, 1986). The uptake rates of ammonium and nitrate by phytoplankton are lower in the dark than in the light, and the nitrate uptake especially seems to
be greatly suppressed under dark conditions (Chang and Campbell, 1978; Healey, 1973; Mitamura and Matsumoto, 1981; Seike et al., 1986a). Relative nitrogen uptake rates by phytoplankton are ammonium > urea > nitrate (Mitamura and Saito, 1986; McCarthy et al., 1977). Based on these findings, the above results in July in this work (Figs. 6c and 8, Tables 2, 4 and 5) might be due to the acceleration of nitrate uptake by phytoplankton resulting from the higher water temperature and the longer daylight, and also by a low concentration of ammonium (cf. Fig. 2).

On the other hand, the significant negative correlation between nitrate concentration and chlorinity in winter season was observed in the present survey for 11 years (Fig. 7 and Table 2). This phenomenon can be explained by the results in our previous paper (Seike et al., 1986a): We have already reported that nitrate uptake by the natural phytoplankton in winter was remarkably suppressed by the lower temperature and the shorter daylight, and also by the preference of phytoplankton for ammonium. (Nitrate is utilized only when the sum of available ammonium and/or urea is insufficient to satisfy the phytoplankton for the demand of nitrogen nutrient.) Therefore, the nitrate supplied from the rivers would be almost unaffected by the phytoplankton uptake. This is a reason why the significant negative correlation between nitrate concentration and chlorinity are observed in winter season (Table 2).

In conclusion, the seasonal variation of nitrate concentration in the surface water of Lake Nakanoumi would be mainly dependent on the following two factors: the amount of nitrate supplied from the rivers into the lake through rainfall and melted snow, and the activity of nitrate uptake by the natural phytoplankton communities.

Acknowledgement

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Table 3. Cumulative rainfall (mm) during the preceding 25 days (1976-1986).

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<td>111</td>
<td>100</td>
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<td>155</td>
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<td>94</td>
<td>106</td>
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<tr>
<td>Maximum</td>
<td>216</td>
<td>162</td>
<td>180</td>
<td>158</td>
<td>163</td>
<td>250</td>
<td>567</td>
<td>227</td>
<td>353</td>
<td>380</td>
<td>176</td>
<td>131</td>
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<tr>
<td>Minimum</td>
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<td>64</td>
<td>41</td>
<td>14</td>
<td>18</td>
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<td>60</td>
<td>39</td>
<td>68</td>
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Table 4. Yearly changes of nitrate concentrations (µgN·l⁻¹) in the surface water at Stas. 20, 3, 15, 4, 13 and 7 in July 1976-1986.

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<td>3</td>
<td>15</td>
<td>139</td>
<td>74</td>
<td>218</td>
<td>7</td>
<td>5</td>
<td>26</td>
<td>10</td>
<td>114</td>
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<td>93</td>
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<td>65</td>
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<td>5</td>
<td>4</td>
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<td>4</td>
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<td>3</td>
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<td>2</td>
<td>2</td>
<td>1</td>
<td>61</td>
<td>6</td>
<td>4</td>
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<td>3</td>
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<td>—</td>
<td>—</td>
<td>2</td>
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<td>3</td>
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Table 5. Yearly changes of cumulative rainfalls (mm) during the preceding 7 and 25 days in July 1976-1986.

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<td>7 days</td>
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<td>9</td>
<td>35</td>
<td>161</td>
<td>120</td>
<td>223</td>
<td>25</td>
<td>12</td>
<td>33</td>
<td>22</td>
<td>76</td>
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<tr>
<td>25 days</td>
<td>58</td>
<td>239</td>
<td>130</td>
<td>242</td>
<td>176</td>
<td>567</td>
<td>60</td>
<td>140</td>
<td>270</td>
<td>452</td>
<td>360</td>
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his critical suggestion.

摘要

汽水湖中海における窒素代謝 IV

硝酸塩の季節変動

汽水湖中海における上層水中の硝酸塩の季節的消長を明らかにするために、中海全域 12 地点について 11 年間（1976～1986）にわたり每月一回の頻度で調査したデータを用い、硝酸塩の供給源、蓄積過程など、その増加をもたらす要因を究明した。

NO₃₋N 濃度は、冬期（1 ～3 月）および梅雨期（7 月）に増加する傾向を示した。対照的に、塩素量はその時期に減少傾向を示した。

NO₃₋N 濃度は、中海湖水の日本海への流出の主流経路とみられる大橋川から境外水にかけて減少傾向を示すとともに、塩素量との間に負の相関性を示した。さらに、NO₃₋N の増加量と累積降水量との関係を梅雨期の 7 月を対象に、流入負荷の影響を受けやすい地点について求めたところ、良好な相関性を示した。これらの結果から、1，2，3 月および 7 月における上層の NO₃₋N 濃度の増加は、主として河川を通じての供給に由来するものと考えられた。

さらに、植物プランクトンによる硝酸塩の利用特性と硝酸塩の蓄積現象との関係についても考察を行なった。

References

TERAI, H. (1988) : Influence of precipitation on development of the denitrification process in
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