 Characteristics of nutrient variation in the brackish Lake Nakaumi, Japan

Yasushi SEIKE*, Kunio KONDO**, Minoru OKUMURA*, Kaoru FUJINAGA* and Katsumi TAKAYASU***

(*Faculty of Science and Engineering, Shimane Univ.; **Institute for Environmental Sciences; ***Research Center for Coastal Lagoon Environments, Shimane Univ.) yseike@riko.shimane-u.ac.jp

1. Introduction

The major nitrogenous nutrients in aquatic environments are nitrate, ammonium and occasionally nitrite. We have studied the uptake of ammonium and nitrate by natural phytoplankton (Seike et al., 1986a), denitrification (Seike et al., 1986b, 1986c), nitrification (Seike et al., 1986c; 1997), the behavior of nitrate (Seike et al., 1990) and nitrous oxide (Senga et al., 2001, 2002) in the brackish Lake Nakaumi, Japan. In the present study, data on nitrogenous nutrients such as nitrate, nitrite and ammonium in the lake were collected monthly during the period May 1990 to April 1998. The present study was undertaken to clarify seasonal variation in inorganic nitrogen compounds in the water column of Lake Nakaumi, on the basis of existing knowledge on nitrogen cycling in the lake. Another aim of the paper is to evaluate the importance of coupled nitrification-denitrification in a water column and water-sediment system, with reference to limiting elements for the growth of phytoplankton in summer in a shallow, stratified, coastal lagoon.

2. Materials and methods

A. Study area and sampling

Lake Nakaumi is located in the northwestern part of the Japanese Archipelago (ca. Lat. 35°30’ N and Long. 133°10’ E). The lake is connected to Lake Shinji by the Ohashi Channel, which is 7.5 km long. It has a surface area of 72 km² and a total storage volume of 3×10⁸ m³. The mean water depth is 5.4 m and about 80 % of the lake is shallower than 7 m. The lake is also connected to the Japan Sea by the Sakai Channel, which is about 0.3 km wide and 7.5 km long.

Observations were carried out at monthly intervals in the central area (6.8 m depth) of Lake Nakaumi, from May 1990 to April 1998. Water samples were collected with a Van Dorn type sampler of 3 L capacity, at about 1 m intervals from the surface down to the bottom. Water samples collected for chemical analysis of nutrients and chlorophyll a (Chl. a) were immediately filtered through glass fiber-filters (Whatman GF/C) preignited at 450 ºC. The filter and filtrates were then stored at -20 ºC in a deep-freezer until chemical analysis in the laboratory.

B. Chemical and physical variables

Ammonium (NH₄-N) was analysed using the indophenol method (Sagi, 1966). Nitrite (NO₂-N) and nitrate (NO₃-N) were analysed using the method of Bendschneider and Robinson (1952) and Wood et al. (1967), respectively. Phosphate (PO₄-P) was determined by the method of Murphy and Riley (1962). Chlorophyll-a (Chl. a) was determined by the SCOR/UNESCO method (1966). Salinity, water
temperature, dissolved oxygen and pH were measured with a multiple water quality sensor (YSI model 3800).

3. Results and discussion

A. Mean seasonal variation of chemical and physical parameters

**Salinity, water temperature, dissolved oxygen and pH**

The seasonal variation in chemical and physical parameters in Lake Nakaumi was investigated by analysis of the data collected monthly during the period May 1990 to April 1998. The mean monthly variation (1990 - 1998) in the vertical distribution of salinity (SAL), water temperature (WT), oxygen saturation (DO), and pH in the central area (Sta. 4) of Lake Nakaumi are shown in Fig. 1. Remarkable decreases of SAL were observed in the upper layer from January to April (Fig. 1a). The variability of SAL was much higher in the upper layer than in the bottom layer. The surface to bottom salinity difference was usually greater than 12.0 psu, averaging 14.9 psu. The halocline, where the vertical salinity gradient is greatest, developed at a depth of 3 to 4 m. It is well known that stable stratification impedes vertical mixing between surface and bottom waters.

The vertical profile of WT shows that the thermal stratification is of minor importance in Lake Nakaumi. Though the annual temperature range was large, extending over 20 °C at each depth, the surface to bottom temperature difference ranged from 1.0 to 4.9 °C throughout the year. Because of the intrusion of warmer saline water through the Sakai Channel into the bottom of Lake Nakaumi, the bottom water became warmer than the surface water during the winter months.

Strong gradients were frequently observed in the vertical profiles of DO and pH directly below the halocline (Figs. 1c, 1d). The oversaturation of DO (100 to 127%) and the high pH values were observed above the halocline as a result of photosynthetic activity, while the lower DO and pH appeared in the water below the halocline from May to November. It appears that the halocline can serve as an effective barrier to the vertical transport of dissolved materials even in this shallow water system, with depths of less than 7 m.

**Inorganic nitrogen species and phosphate phosphorus**

Mean monthly variation (1990 - 1998) in the vertical distribution of ammonium (NH$_4$-N), nitrite (NO$_2$-N), nitrate (NO$_3$-N) and phosphate (PO$_4$-P) at Sta. 4 is summarized in Fig. 2. The NH$_4$-N concentrations were low in the euphotic layer (0 - 3 m), while the concentrations were very high near the bottom. Higher NO$_3$-N values were observed in the entire water column from January to April and in the upper layer in July. The highest value, 126µgN l$^{-1}$, was obtained at 0 m depth in March. In contrast to NH$_4$-N, these values were much higher in the surface layer than in the bottom layer. The accumulation of NO$_3$-N was mainly caused by discharge of rainfall and melted snow via rivers into the lake (Seike et al., 1990). From an experiment using the $^{15}$N tracer technique, the uptake rates of NH$_4$-N and NO$_3$-N by phytoplankton were lower in the dark than in the light, and the NO$_3$-N uptake was greatly suppressed in the dark (Seike et al., 1986a; Mitamura and Matsumoto, 1981). NO$_3$-N was utilized only when the sum of available NH$_4$-N was insufficient to meet phytoplankton demand for the nutrient nitrogen (Seike et al., 1986a; Mitamura and Saijo, 1986). Thus NO$_3$-N uptake by phytoplankton in winter was greatly reduced.
due to the lower temperature and the shorter period of daylight; and also by the preference of phytoplankton for NH$_4$-N. This is the reason why NO$_3$-N accumulation in winter, that is, the NO$_3$-N supplied from the rivers, is almost unaffected by phytoplankton uptake. Interestingly, high concentrations of NO$_2$-N, exceeding 40µg N L$^{-1}$, were found in the hypolimnion from August to September.

The concentration of PO$_4$-P remained at low levels from January to April, but increased gradually in the bottom water below the halocline until October, reaching a concentration of 128µg P L$^{-1}$ (Fig. 2b). The concentration of PO$_4$-P showed distinct seasonal cycles with high values in the bottom water below the halocline during summer months. PO$_4$-P disappeared in the upper layer above the halocline from December to June. However, a small but significant amount of PO$_4$-P remained in the upper water from July to November. The PO$_4$-P in the upper water seems to have been supplied from the bottom water.

Chlorophyll-α

Chlorophyll-α (Chl. α) concentrations were higher in December and in February (Fig. 3). During May 1990 to April 1998, high values exceeding 100µg L$^{-1}$ were observed three times: in January 1995, February 1997, and December 1997. The maximum Chl. α concentration, 273µg L$^{-1}$ was recorded at 1 m depth in February 1997. These large concentrations were almost entirely due to populations of the dinoflagellate *Prorocentrum minimum* and the small diatom *Skeletonema costatum*. *P. minimum* and *S. costatum* are the representative causative species of red tide in Lake Nakaumi. Kondo et al. (1990a) reported that *P. minimum* red tides occurred from December to April when water temperature was low; and that they had never been observed in summer between 1974 - 1984. It seemed, at first sight, strange that a *P. minimum* red tide has not occurred in summer when temperatures are favorable for its growth in Lake Nakaumi, as pointed out by Kondo et al. (1990a, 1990b).

B. Vertical profiles of chemical and physical parameters

Nutrients (N, P), chlorophyll-α and physico-chemical parameters in summer

Vertical profiles of inorganic nitrogen (I-N), PO$_4$-P and Chl. α at Sta. 4 from July to October in 1997 are shown in Figs. 4a1, 4a2, 4a3 and 4a4. Vertical profiles of SAL, WT, DO and pH at Sta.4 for the same dates are also shown in Figs. 4b1, 4b2, 4b3 and 4b4.

On 6 August, increases in NO$_3$-N and especially NO$_2$-N with a decrease in NH$_4$-N were found in the water below the halocline (Figs. 4a1 and 4a2). At the same time, an increase in DO, an increase in pH, and a decrease in total inorganic nitrogen (TIN) and PO$_4$-P were observed in the overlying water (Figs. 4a3 and 4a4). Such increases in DO and pH are derived from the intrusion of seawater which is higher in DO and pH. Temporal decrease in TIN (NH$_4$-N + NO$_2$-N + NO$_3$-N) and PO$_4$-P at 6 m depth are also due to dilution by seawater. DO supplied into the overlying water could be easily diffused to 5 m depth because there is little difference in SAL between the depths of 5 and 6 m. Tidal currents, that is, the flood and ebb currents are commonly repeated two times per day during neap tides or four times per day during spring tides, respectively. Thus, these results imply that the increase in NO$_3$-N and NO$_2$-N in the hypolimnion was mostly due to nitrification induced by the increase of DO, supplied by seawater inflowing on the tidal current.
On 3 September, the concentration of PO₄-P in the bottom water increased greatly to values of 124µgP L⁻¹ (Fig. 4a₁). The release of PO₄-P from the bottom sediment is clearly responsible for the increase in PO₄-P in summer. The PO₄-P concentration in the surface water also increased gradually from July to September, reaching a mean concentration of 39µgP L⁻¹ at 0-3 m depth (Figs. 4a₁, 4a₃, and 4a₅).

In contrast to PO₄-P, the TIN concentration in the bottom water substantially decreased from July to September. It seems that nitrification-denitrification resulted in the decrease of TIN in the hyplimnion on 3 September.

The Chl. a concentration varied in the range of 3.2 to 16.2µg L⁻¹ in the upper layer, 0 to 3 m depth, from 10 July to 3 September. Chl. a at a depth of 1 m was 16.2µg L⁻¹ on 10 July and decreased gradually until 3 September, reaching a low concentration of 4.2µg L⁻¹. On 1 October, however, the Chl. a concentration increased markedly in the upper layer (0-3 m), reaching a high concentration of 32.0µg L⁻¹ at 3 m depth (Fig. 4a₄). Precipitation in September 1997, 394 mm was about twice the normal value. From the decrease in SAL from 3 Sept. to 1 Oct., it seems likely that a large amount of nitrogen nutrients were delivered to the lake through discharge from rivers. It may be noted that the increase of the Chl. a concentration on 1 October was induced by an increase in available nitrogen, which was supplied through river discharge.

Reference


Fig. 1. The depth-time mean distributions of SAL (a), WT (b), DO (c) and pH (d) in the central area of Lake Nakaumi (Sta. 4) from January to December. Using data; May 1990 to April 1998.

Fig. 2. The depth-time mean distributions of I-N (a) and PO₄-P (b) at Sta. 4 from January to December. □, NH₄-N; □, NO₂-N; □, NO₃-N. Using data; May 1990 to April 1998.
Fig. 3. The depth-time mean distributions of Chl. a at Sta. 4 from May 1990 to April 1998.

Fig. 4. a) Vertical profiles of inorganic nitrogen (I-N), phosphate phosphorus (PO₄-P) and chlorophyll a (Chl. a) at Sta.4. , NH₄-N; , NO₂-N; , NO₃-N; , PO₄-P; , Chl. a.
b) Vertical profiles of salinity (SAL), water temperature (WT), dissolved oxygen saturation (DO) and pH at Sta.4. , SAL; , WT; , DO; , pH.

Sampling date: 10 July (a1, b1), 6 August (a2, b2), 3 September (a3, b3) and 1 October (a4, b4) in 1997.