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The Limnological Survey of a Coastal Lagoon in Korea (2): Lake Hyangho

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동해안 석호의 육수학적 조사 (2): 향호. 허우명* · 권상용[1] · 이재일 · 김동진[2] · 김범철[1] (삼척대학교 환경공학과, [1]강원대학교 환경학과, [2]원주지방환경청)

향호의 육수생태학적 특성에 관한 조사를 1998년 5월부터 2002년 11월까지 겨울을 제외하고 2개월 간격으로 실시하였다. 수온, 염분, 투명도, 총질소, 총인, 및 퇴적물의 유기물량과 같은 물리 화학적인 조사와 엽록소 *a* 농도, 식물플랑크톤 우점종 및 밀도 변화 등과 같은 생물 조사를 병행 하였다. 향호에서 화학성층은 2～5 m 수심에서 관측되었으며, 용존산소 농도 및 수온분포에 영향을 주는 것으로 나타났다. 염분이 높은 수층에서 용존산소의 농도가 낮았으며, 수직혼합의 제한으로 11월에는 심층에서 표층보다 약간 높은 수온 역전현상이 관측되었다. 투명도는 0.1±0.0～0, 1 m로 매우 낮은 수준이였다. 표층에서 총인, 총질소 및 엽록소 *a* 농도는 각각 0.011～0.238 mgP L^{-1}, 0.4～2.4 mgN L^{-1} 및 0.7～145.2 mg m^{-3}이였다. TN/TP 비는 대부분 30 이하였으나, 총질소와 총인 농도는 높았다. 퇴적물의 입자크기는 0～125 μm로 silt와 coarse silt이였다. 퇴적물의 화학적산소요구량, 총인 및 총질소는 각각 19.7～73.3 mgO_2 gdw^{-1}, 0.61～1.32 mgP gdw^{-1} 및 0.64～0.88 mgN gdw^{-1}의 범위이였다. 식물플랑크톤은 시기에 따라 차이는 있으나 녹조류인 *Ankistrodesmus falcatus*, 남조류인 *Oscillatoria* sp. 및 *Merismopedia tennuissima* 등이 우점하였다. 총 세포수는 560～35,255 cells mL^{-1}의 범위로 계절적으로 큰 차이를 보였다.

Key words : Lake Hyangho, brackish lagoon, trophic state

INTRODUCTION

The brackish lagoons of the eastern coast of Korea were generated by sand dunes. The tidal inlet for water exchange led the lagoon water into a poor flushing condition resulting in salinity of over 0.5% and thus enabling us to rank the water as brackish water (Horne, 1994). So, due to the demoted water exchange, well-developed aquatic plants were found in the littoral zone. The lagoon's brackish water is characteristically different from inland fresh water thus limiting vertical mixing and causing anaerobic layer in hypolimnion despite the shallow depth. In some shallow lagoons of the eastern coast of Korea, winds are responsible for the upward movement of organic matter from anaerobic hypolimnion to epilimnion and thus driving the latter into an oxygen-deficient condition (Kwon, 2002). In lagoons, a unique ecological interaction is found, as organisms of brackish water, seawater, and fresh water coexist (Wonju Regional Environmental Office, 1997). Also, the exchange of fresh

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water and seawater make brackish water an interesting ecological place (Hong, 1969). But, in brackish lakes, the organisms are not homogenously distributed (Pyen, 1984). As there is not much competition, nutrient-rich brackish water is a proper place where each individual benthos shows a very fast growth once they are adopted (Kim, 1997). Due to the high fluctuations in the concentrations of salinity, a few species with a larger tolerance range thrive when aided by the periodical inflow of nutrients. The lagoons in the eastern coast of Korea have significant value from the tourism point of view as well as from the conservation point of view, due to the insufficient number of natural lakes and marshy ecosystems (Heo *et al*., 1999).

Lake Hyangho is a small semi-closed lagoon located on Hyanghori, Gangrung in the eastern costal region of Korea. It has a total surface area of 0.345 km^2, maximum depth of 14 m, hydraulic retention time of 1.3 year, drainage area of 8.06 km^2, and has water capacity of 14.45 million tons. The inflowing stream to Lake Hyangho has its origin in the mountains, which have an altitude of about 306 m and a base of fine alluvial shoreline plain. With the common upper stream area as that for Reservoir Hyanghori, the inflowing stream to Lake Hyangho has a total length of 16.86 km (Ministry of Environment, 2001). Originally, Lake Hyangho had a maximum depth of 2.69 m (Cho *et al*., 1975; Pyen, 1984), but due to the gradual extraction of silica from it, the present maximum depth is 14 m and the untreated inflowing water has severely affected the water quality. The original size of the lagoon has reduced in size because the shoreline areas were reclaimed to grow rice paddies and the subsequent increased accumulation of high sediment loading from the surrounding areas. During the first half-decade of 1990s, Lake Hyangho lured migratory birds such as swan, white heron, and dew, which was an attractive (winter) stopover, with it's good water quality (Wonju Regional Environmental Office, 1997).

The research on Lake Hyangho was mostly for short time periodsand primarily motivated towards collecting basic data of fish farms (Cho *et al*., 1975; Kim *et al*., 1981; Pyen, 1984). Studies on the concentrations of chlorophyll-*a* and TP showed that most of the natural lakes of the eastern coast of Korea were hyper-eutrophic. Heo *et al*. (1999) highlighted that Lake Hyangho and six other brackish water lagoons were in serious eutrophic condition.

This study of Lake Hyangho was carried out from May 1998 to November 2002 on a two-month interval basis to find out the limno-ecological characteristic. Various physico-chemical parameters including temperature, salinity, Secchi disc transparency, TN, TP, organic matter in sediment, and chlorophyll *a* concentration were measured. Changes of dominant species and cell density of phytoplankton were also surveyed.

METERIALS AND METHODS

Lake Hyangho, located in the northern region of Gangrung, has an average yearly precipitation of 1,400 mm and the yearly average air temperature of 12.9°C. From June to September, about 60～70% of yearly precipitation are recorded. In August 2002, the highest monthly precipitation of 1,137.0 mm per month was observed (Fig. 1). N and P generation in the drainage area was 147 kgN day^{-1} and 28 kgP day^{-1} respectively (Heo *et al*., 1999). Samples collected from 1998 to 2002, were filtered with CF/C filter paper in the lab. The filter papers were kept frozen, and homogenized at the time of chlorophyll-*a* analysis. Lorenzen's (1967) method was used to calculate chlorophyll-*a* concentration. Filtered water was then used to calculate dissolved nitrogen and phosphorus. TP was determined according to Standard methods (APHA, 1992), employing persulfate digestion and ascorbic acid method. TN

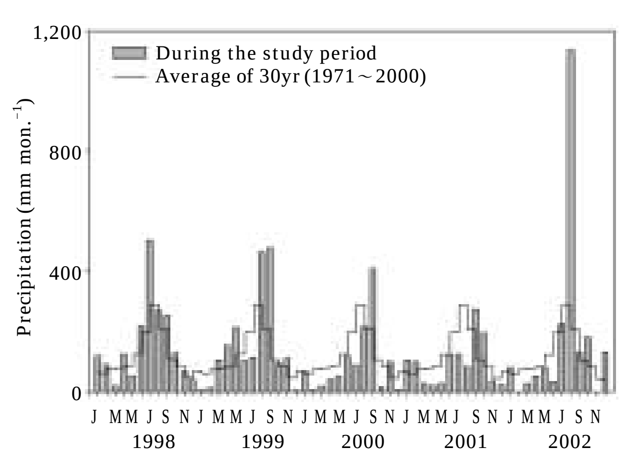

Fig. 1. Monthly variations of precipitation of Gangnung.

was determined by the cadmium reduction method after persulfate digestion, using a flow injection autoanalyzer (BRAN+LUEBBE, Auto Analyzer3). Temperature and salinity were measured with a multiprobe meter (YSI, 6000). Trophic State Index (TSI) was calculated according to Carlson (1977).

RESULTS AND DISCUSSION

1. Temperature, Salinity, Dissolved Oxygen and Secchi Disk transparency

The average temperature of lagoon water was 18.9±7.6°C with the maximum being 30.9°C and the minimum 8.3°C. As Lake Hyangho froze in winter, the minimum temperature could not be obtained. The yearly temperature distribution did not show much variation. The concentration

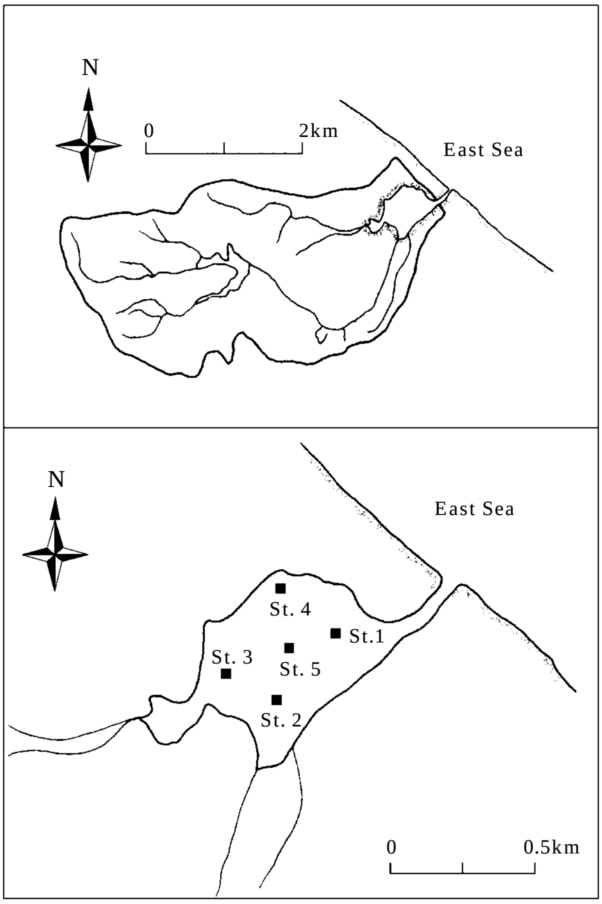

Fig. 2. Showing the watershed and sampling site of Lake Hyanho.

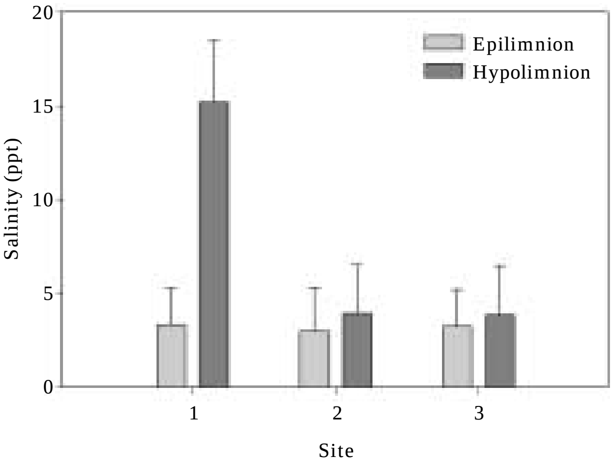

Fig. 3. Horizontal variations of salinity.

of salinity in epilimnion, in most parts of the lagoon, ranged from of 0.8~8.8‰. Distribution of salinity was influenced by seawater permeation, which is implied by higher salinity in the bottom water. The mean salinity remained fairly constant at most sampling stations with the exception of Site 1 where abnormal high concentrations of 15‰ was found in the hypolimnion (Fig. 3). There was smaller variation of salinity during the rainy months of August and September (0.2~4.3‰), while larger variation was observed in October and November of 3.3~5.0‰ and 15.2~15.9‰ (Kim *et al.*, 1981). From February till June, a moderate salinity range of 12‰ was found, but in August, average dropped to 2‰ (Pyen, 1984).

Due to the relatively good flushing condition in the outer lagoon (area near the outlet to the sea), seasonal vertical distribution of temperature at site 1 showed very small difference of about 5°C during March and May 2001. In July, thermocline was formed with the temperature at epilimnion and hypolimnion being 28°C and 13°C, respectively. But in November, metalimnion showed a higher temperature of 16°C, while the epilimnion and hypolimnion being 11°C, and 13 °C, respectively (Fig. 4). The epilimnion and hypolimnion could not mix vertically, thus forming a strong chemocline in the metalimnion (Heo, *et al.*, 1999; Kwon, 2002). During the period of survey, at site 1, at depths of 2~5 m, strong chemocline was formed due to high salinity and limited vertical mixing. Because of this stable water layer, anaerobic conditions in the hypolimnion were maintained resulting in prolonged

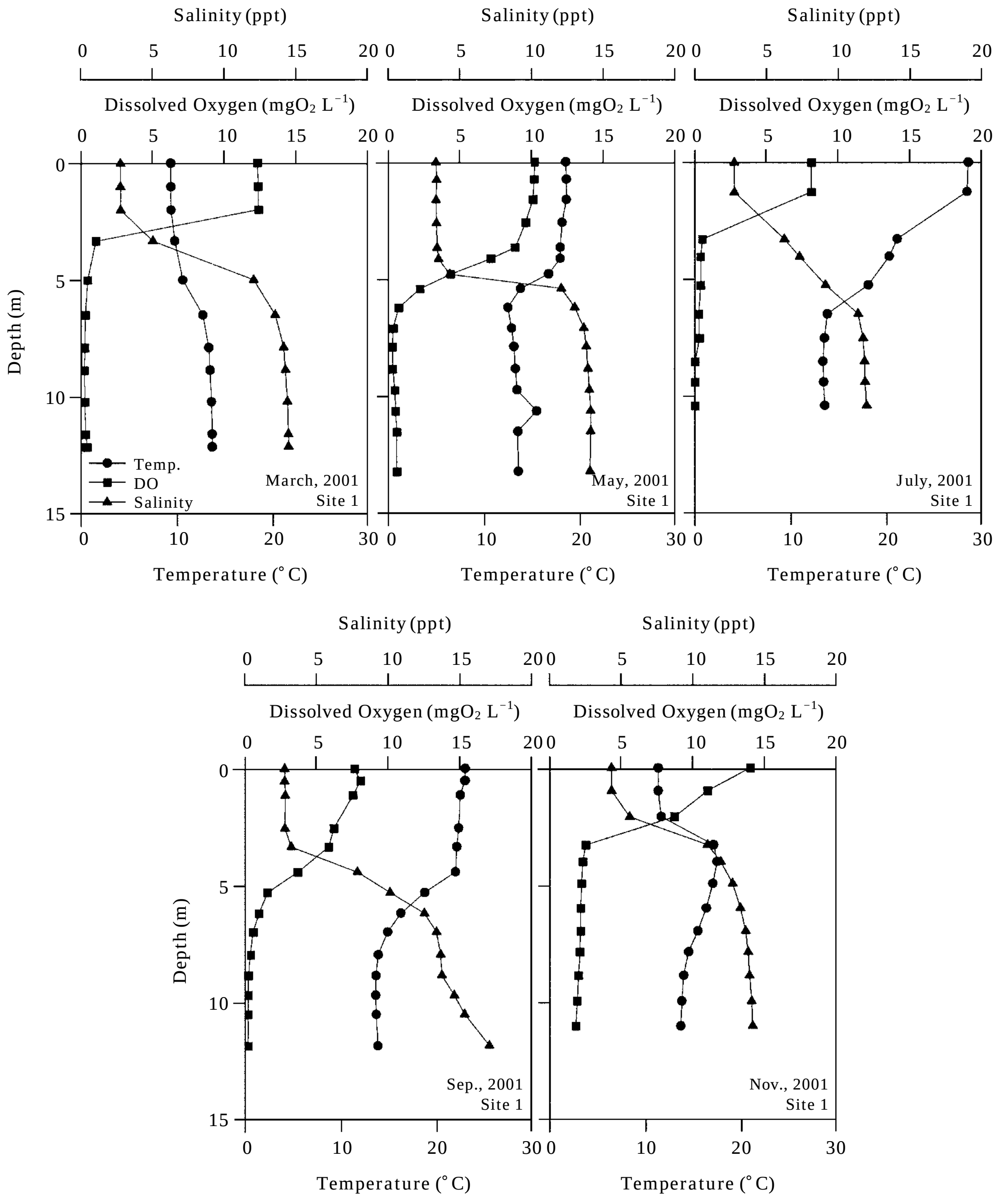

Fig. 4. Seasonal variations of vertical distribution on temperature, dissolved oxygen, and salinity at the site 1, from March to November, 2001.

organic decomposition duration. The most important factors in lagoons are stratification and destratification of freshwater (Schroeder *et al.*, 1990), which are affected by wind, seawater intrusion, and freshwater inflow (Uncles *et al.*, 1990). The DO concentrations were lower in the inner lagoon than in the outer lagoon, and in the bottom water than in the surface water for the stratified seasons. Water was stratified particularly in the inner lagoon during warm seasons, when the freshwater input was significant, and salinity and temperature differences between the bottom and surface were much larger in summer than in winter. In general, DO concentrations were also lower in summer than in winter. In addition to poor flushing rate and stratified condi-

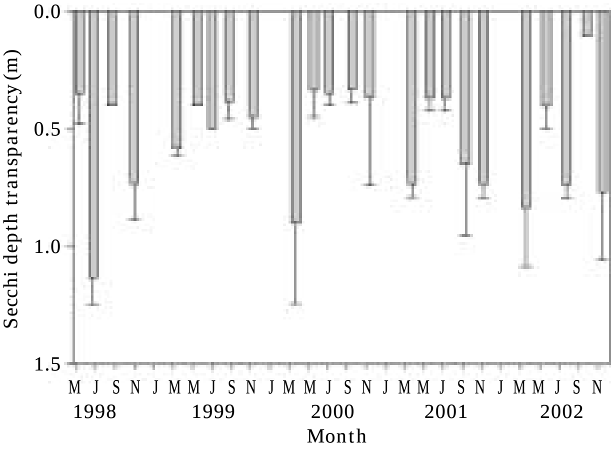

Fig. 5. Seasonal variations of Secchi disc transparency at the all site.

tions, high primary productivity and respiration rates may also be responsible for driving the water into oxygen−deficient conditions. The distribution of DO concentrationis also greatly affected by salinity. In 2001, DO concentration in the epilimnion was 10 $mgO_2\ L^{-1}$ all around the year at Site 1, but from March to September DO depletion was found below the depths of 3∼5 m. In November, DO concentration below the depth of 3 m was as low as 2 $mgO_2\ L^{-1}$. DO concentration was low below the chemocline, because salinity reduced solubility and DO was consumed in the decomposition of organic matter. Also the chemocline consistently existed and vertical mixing was limited, thus enhancing anaerobic condition in hypolimnion. In July, anaerobic conditions were maintained below 2 m, which was a serious limiting factor to the distribution of benthos (Kim *et al.*, 1981). In most of lagoons on the eastern coast of Korea, chemocline is formed in methalimnions, resulting in DO depletion in hypolimnions. Chemocline formation is a common phenomenon in lakes with anaerobic conditions in hypolimnion (Heo *et al.*, 2001; Kwon, 2002). But at depths of 1 m range there was not much difference in hypolimnion and epilimnion at Sites 2 and 3.

The seasonal variation of the Secchi disk transparency was 0.1±0.0∼1.1±0.1 m, which is very low (Fig. 5). Particularly in September 2002, very low Secchi depth of 0.1 m was found, which might be due to the inflow of storm water. In most of the lagoons on the eastern coast of Korea, Secchi depth was low, which wasdue to the high inor-

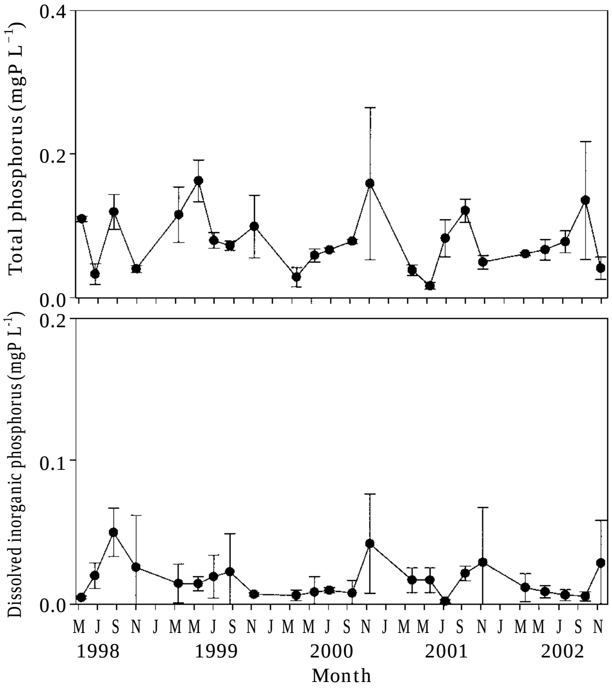

Fig. 6. Seasonal variations of TP and DIP concentration at the all site.

ganic particle concentration, besides phytoplankton blooms (Heo *et al.*, 1999). In the study of Lake Hwajinpo, phytoplankton blooms and loading of soil has also resulted in low Secchi depth (Kwon, 2002). Secchi depth was low at sites 2 and 3 but downstream there was not much difference.

2. Nutrient and trophic state

Concentrations generally increased from the outlet towards the inner basin, with higher concentrations in bottom water than in surface water, which resulted mainly from the biological uptake of nutrients in the surface and regeneration of organic matter in the bottom. Meanwhile, nutrient concentrations were lower in warm seasons than in the winter seasons due to higher productivity in warm seasons. The seasonal variations of TP and DIP in the epilimnion after the rainy seasons (September−November) were high. During the survey period, TP and DIP concentrations in the epilimnion were 0.011∼0.238 $mgP\ L^{-1}$ and 0.001∼0.078 $mgP\ L^{-1}$, respectively. TP and DIP at site 3, in November 2000, were very high (Fig. 6). Generally, in the case of Korean lakes, concentrations of P increase in rainy seasons (Heo *et al.*, 1992). The evaluation of trophic

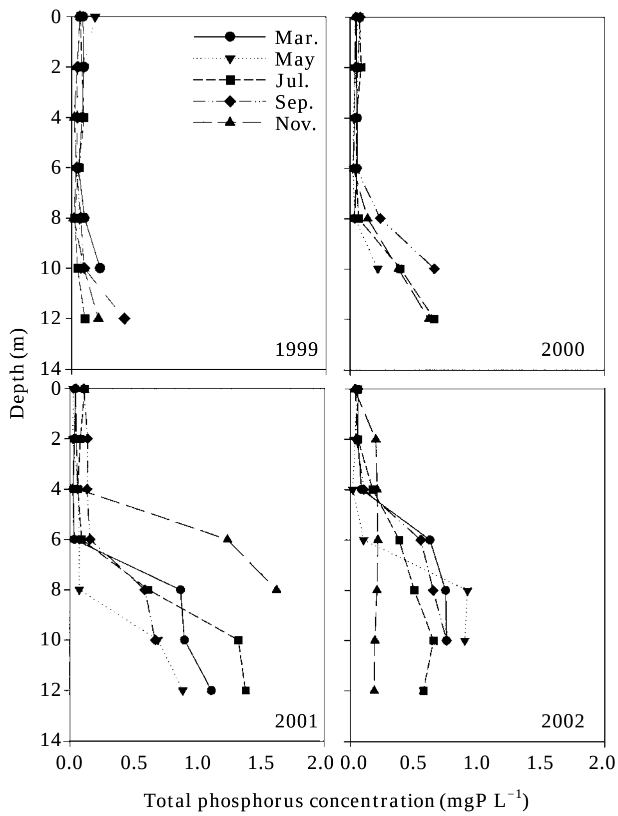

Fig. 7. Vertical variations of TP concentration at the site 1.

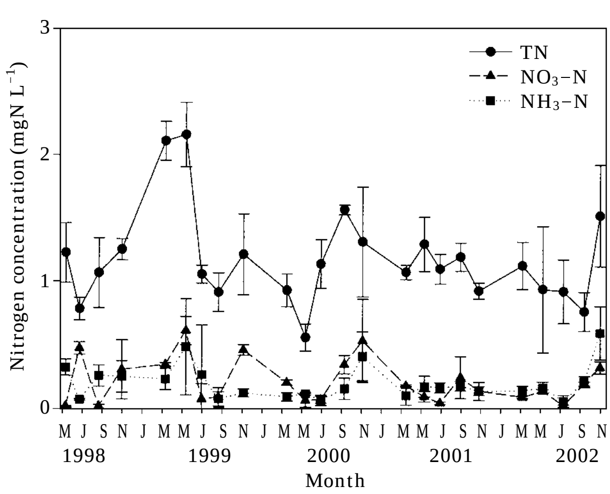

Fig. 8. Seasonal variations of TN, NO_3-N, NH_3-N concentration at the all site.

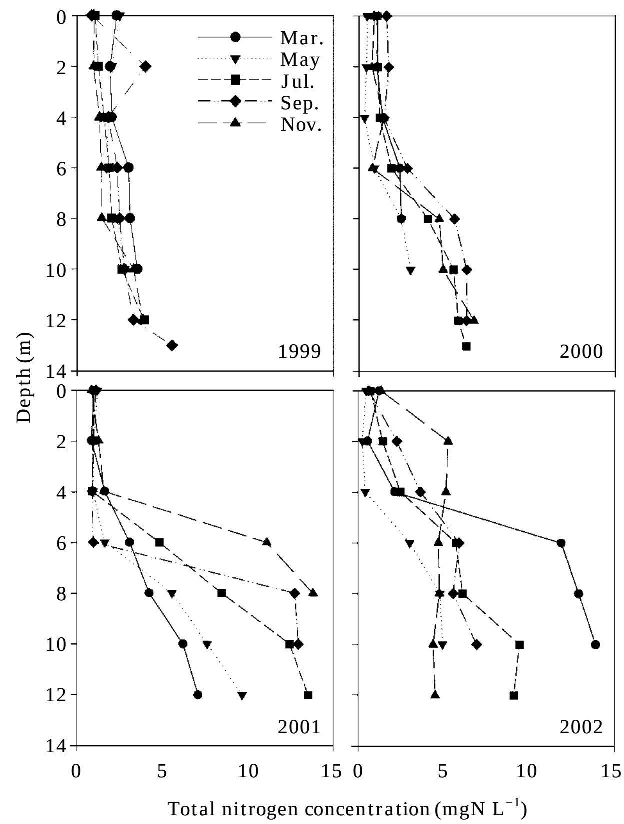

Fig. 9. Vertical variations of TN concentration at the site 1.

state in the eastern coast of Korea showed a decrease in phosphorus concentration in rainy seasons, because many regions were affected by seawater, as was the case for Lake Hyangho (Heo *et al.*, 1999). During the survey period, average TP concentration was 0.079 mgP L^{-1}, which is much higher than the eutrophication standard suggested by U.S. EPA (1976) of 0.020 mgP L^{-1}. DIP concentration on average was 0.016 mgP L^{-1}. TP vertical distribution showed high concentrations below metalimnion (Fig. 7). At site 1, in November 2001, high differences in TP concentration were found with the epilimnion being 0.040 mgP L^{-1} and the hypolimnion being 1.621 mgP L^{-1}. High concentrations of TP were found in thehypolimnion because of (i) longer hydraulic retention time, (ii) increased sediment loading from the inflowing stream, (iii) increased primary production and respiration rate, and (iv) anaerobic conditions (Kwon, 2002).

In May 1999, TN in the epilimnion was 2.2$\pm$0.3 mgN L^{-1}, which was high during the survey time (Fig. 8). During that time, NO_3^--N and NH_3-N concentrations were 0.6$\pm$0.1 mgN L^{-1} and 0.5$\pm$0.4 mgN L^{-1}, respectively. The vertical distribution of TN was higher below the depths of metalimnion (Fig. 9). Particularly, in March

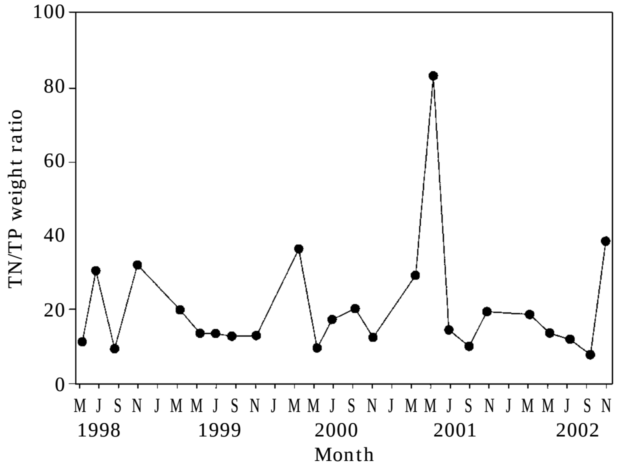

Fig. 10. Seasonal variations of TN/TP weight ratios.

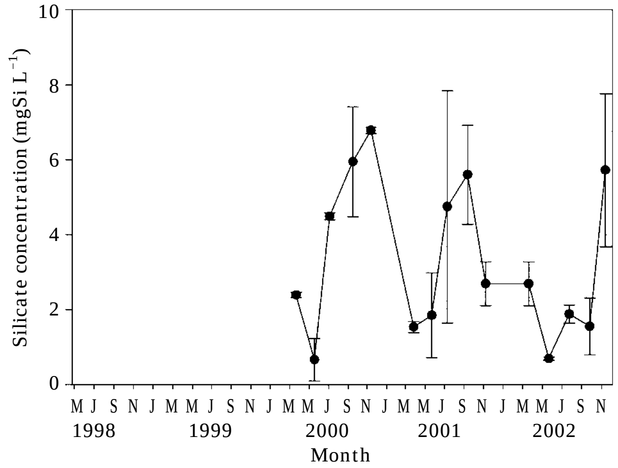

Fig. 11. Seasonal variations of silicate concentration at the all site.

2002, the TN concentration was 13.9 mgN L^{-1} at Site 1, which is very high. At the same time, NH_3-N concentration was 9.0 mgN L^{-1}, which shows higher percent of NH_3-N in TN (i.e. anaerobic hypolimnion formation for anaerobic decomposition is high in comparison with epilimnion) (Kwon, 2002). The TN/TP weight ratio was usually below 30. Generally the TN/TP ratio has a low value, which is due to the higher concentration of phosphorous compared to nitrogen. So, to protect lake from eutrophication, phosphorus loading needs to be reduced. In May 2001, the TN/TP ratio was as high as 103 at Site 3, and it was 65 and 80 at Site 1 and 2, respectively (Fig. 10).

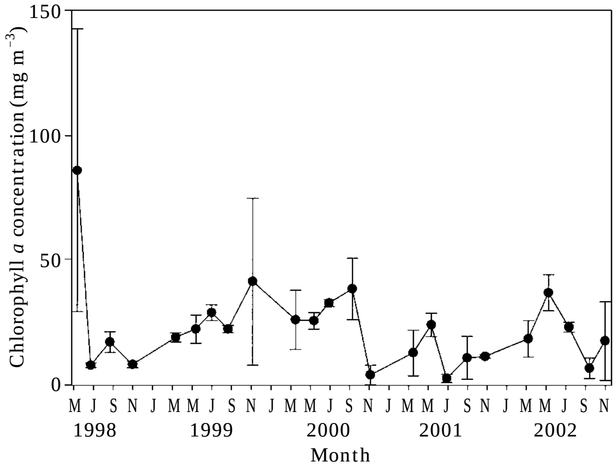

Fig. 12. Seasonal variations of chlorophyll *a* concentration at the all site.

In the case of major Korean reservoirs, TN/TP ratios are usually 40~160, and for estuaries 20~30 is reported (Kim *et al.*, 1997). Most lagoons of the eastern coast of Korea have a low TN/TP ratio of 6~14 (Heo *et al.*, 1999). When this data is compared, Lake Hyangho seems to have a lower level than in estuaries. Due to P and N concentration is usually high, algal growth is not thought to be limited by nutrient depletion (Heo *et al.*, 1999). TP was over 30 mgP m^{-3} and TN was over 1.1 mgN L^{-1} (Likens, 1975). Vollenweider (1968) suggested TP of 10 mgP L^{-1} and DIN of 300 mgN L^{-1} as the standard for eutrophic state. By this standard, Lake Hyangho is classified as hyper-eutrophic. Silicate concentrations at each site ranged from 0.00 to 8.20 mgSi L^{-1} (Fig. 11). In spring, decreased concentrations of silicate (1.0 mgSi L^{-1}) were found, thus regarding it as a limiting factor, for growth of diatoms rather than DIN and DIP.

Average chlorophyll *a* concentrations in the epilimnion ranged 2.6±1.7~86.0±56.7 mg m^{-3} in May 1998 in all sites (Fig. 12). In the epilimnion, yearly averages of chlorophyll *a* concentrations in '98, '99, '00, '01 and '02 were 29.8, 26.7, 25.4, 12.4, and 20.6 mg m^{-3}, respectively. The U.S. EPA guideline (1976) for chlorophyll *a* concentration in eutrohic conditions is 10 mg m^{-3}. The Forsberg and Ryding's guideline (1980) is 40 mg m^{-3} for hyper-eutrophication. From these classifications, Lake Hyangho is classified as a eutrophic lake.

The TSI of Lake Hyangho was yearly average

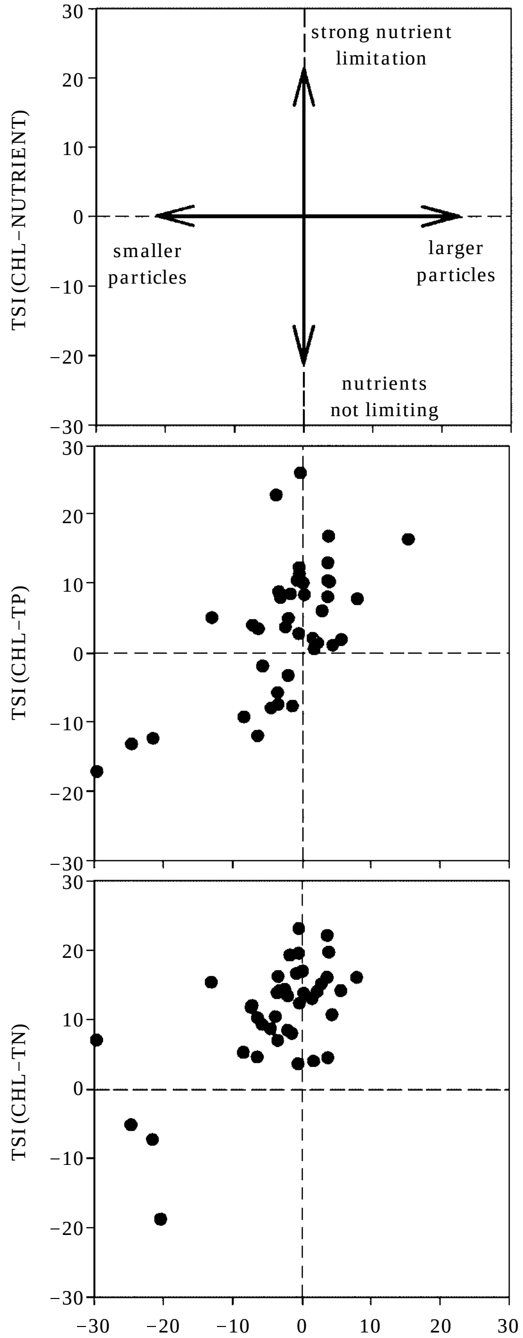

Fig. 13. Differences among trophic state index (TSI) values indicate both the degree of nutrient limitation and the composition of seston.

range of 65∼68 (Table 1). TSI of the Secchi disk transparency and TP in 2002 were very high and TSI of chlorophyll *a* in 2000 was very high. In 2001, the TSI was a little low compared with the results of other years. A eutrohic river system in Korea, the Nakdong River, showed a similar trophic state with TSI of 59∼77 (Heo, 1999). Heo *et al.* (2001) reported that Lake Chungcho had a TSI range of 59∼77 and Kwon (2002) pointed out that Lake Hwajinpo had a TSI of 63∼74. TSI of Lake Hyanho was similar to Lake Chungcho and Lake Hwajinpo. Haven's (2000) method proposed that nitrogen is limiting nutrient factor for phytoplankton growth in Lake Hyangho (Fig. 13). With the fine dispersal of small sized particles in the water column, light transmission could have also beena possible limiting factor for algal growth.

Table 1. TSI: trophic state index (Carlson, 1977). TSI was calculated from warm season average by surface water.

	TSI				Average
	SD	CHL	TP	TN	
1998	69	70	66	57	65
1999	72	71	70	59	68
2000	76	73	65	57	68
2001	72	58	61	59	63
2002	77	68	68	56	67

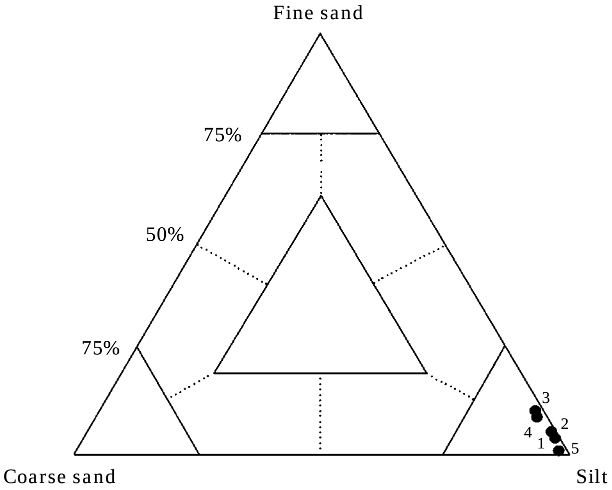

Fig. 14. The texture of sediment in Lake Hyangho.

3. Sediment

The water content of sediment at each site ranged from 44.4∼63.9% and had relatively low sediment depths near the areas of inflowing streams and tidal inlet points. Surface sediment samples mostly consisted of a mixture coarse silt, silt, and fine particles sized 0∼125 μm (Fig. 14).

Table 2. Water content and nutrient concentration of sediment in Lake Hyangho.

Site	Water content (%)	Org. matter content (%)	COD (mgO_2 gdw^{-1})	TN ($mg\ gdw^{-1}$)	TP ($mg\ gdw^{-1}$)
1	60.4	6.6	19.7	0.66	0.85
2	44.4	5.1	59.3	0.75	0.61
3	46.9	6.5	73.3	0.88	0.72
4	63.9	6.8	41.1	0.72	1.32
5	55.0	7.5	61.3	0.64	1.00

In the outlet and inlet areas of the lagoon, relatively greater grain size distribution of particles was found, which is due to erosion, deposition of organic matter, and debris of dead plants, aquatic plantsand microorganisms. COD of sediment showed high range (19.7 ~ 73.3 $mgO_2\ gdw^{-1}$), which was due to the sedimentation of organic debris from the inflowing stream, and the bloom of phytoplankton. The average organic matter concentration of sediment was 6.4%. Average of sediment TP was 0.90 $mgP\ gdw^{-1}$ at Site 4, and sediment TN was 0.7 $mgN\ gdw^{-1}$ at Site 3 (Table 2). In the study of Jun and Kim (1990), they noted that a lake sediment with TP of 0.46 ~ 0.81 $mgP\ gdw^{-1}$ mostly consisted of NAI−P and Res−P. When it is compared with the sediment TP of Lake Hyangho, the latter showed higher concentrations.

4. Phytoplankton

During the survey period, a total of 67 species of phytoplankton were found and Cyanophyta was predominant. Usually, during July to September, higher biomass was found and was commonly dominated by Cyanophyta. In July 2002, the total biomass was 560 ~ 32,255 cells mL^{-1}, the dominant species was *Merismopedia tennuissima* (biomass 17,902 cells mL^{-1}), and subdominant species was *Phormidium* sp. with a biomass of 15,815 cells mL^{-1}. Oscillations in dominant species were found in 1998 & 1999 by Cyanophyta *Oscillatoria* sp., in 2000 by Chlorophyta *Chlorella* sp., and in 2001 and 2002 by Cyanophyta *Merismopedia tennuissiman*. *Particularly* in the case of Lake Hyangho, Chlorophyta *Ankistrodesmus falcatus*, Cyanophyta *Oscillatoria* sp. and *Merismopedia tennuissiman* were the most common dominant species (Fig. 15).

Cyanophyta was mostly dominant in shallow area where the nutrients in the lake sediment

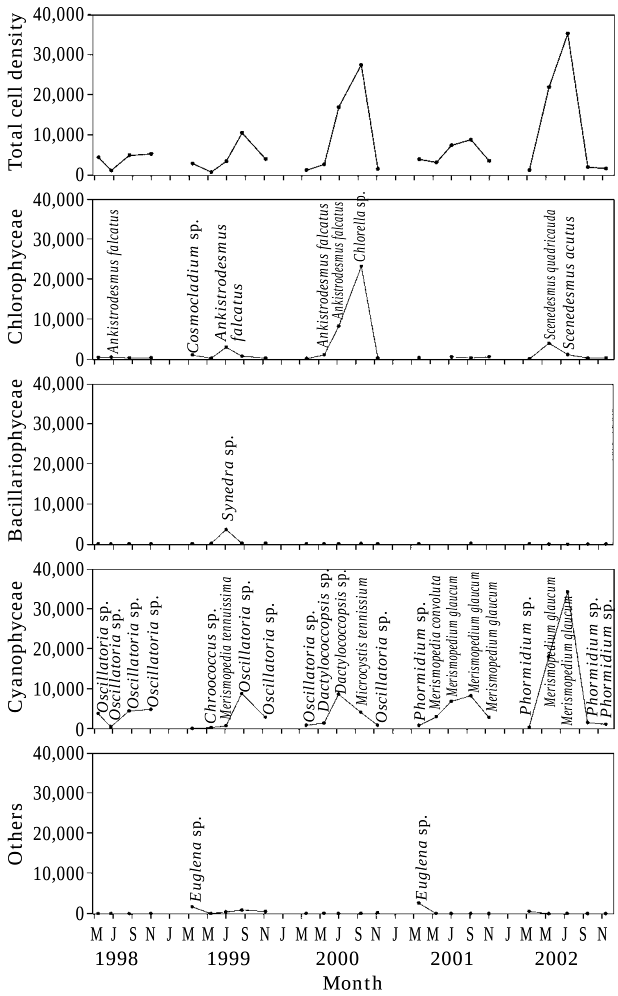

Fig. 15. Cell density and dominant species of phytoplankton.

were easily accessible and were usually resuspended by waves, thus resulting in an increased cell density of phytoplankton. Generally, nitrogen depletion and eutrophication occurs due to the bloom of Cyanophyta (Tezuka, 1988). In Lake Hyangho, the diversity and distribution of species was somewhat low but had high cell density. The diversity of species was static but the abundance of nutrient allowed a high growth rate for each species and also permitted massive growth of individuals, which make them less prone to predators (Kim, 1997). During each survey, higher biomass discrepancies were noted which may have been due to the small size of the lagoon, wind, temperature, and other in−situ as well as ex−situ environmental gradients. Kim (1981) reported that *Thalassiothrix frauenfeldii*, *Navi-*

cula placentula, Amphora hyaline, Chaetoceros costatus, and *Cocconeis scutellum* were dominant species, where the marine species compromised as much as 56.0%. On the contrary those marine diatoms were not found in this study, provoking a contrasting conclusion.

ABSTRACT

The limnological characteristics of a coastal lagoon were studied in Lake Hyangho, one of a series of brackish lagoons along the eastern coast of Korea. Phytoplankton community structure, physical factors, and chemical factors were surveyed from May 1998 through November 2002 on a two-month interval basis. Temperature, salinity, Secchi disc transparency, TN, TP, organic matter content of sediment, chlorophyll *a* concentration, dominant phytoplankton species, and phytoplankton cell density were measured. Salinity gradient was formed between the overlying freshwater stream water and the permeated seawater at the bottom. The chemocline was persistent at the depth of 2～5 m that caused discontinuities of salinity, DO, and temperature profiles. The inversion of vertical temperature profiles with higher temperature in deeper layer was observed in early winter. Secchi disc transparency was very low with the range of 0.1 to 1.1 m. TP, TN, and Chl. *a* concentration in the epilimnion was 0.011～0.238 mgP L^{-1}, 0.423～2.443 mgN L^{-1}, and 0.7～145.2 mg m^{-3}, respectively. Sediment was composed of silt and coarse silt. COD, TP, and TN content of dry sediment were 19.7～73.3 mgO_2 g^{-1}, 0.61～1.32 mgP g^{-1} and 0.64～0.88 mgN g^{-1}, respectively. Dominant phytoplankton species were chlorophytes (*Ankistrodesmus falcatus*) and cyanobacteria (*Oscillatoria* sp. and *Merismopedia tennuissima*). The total cell density was in the range of 560～35,255 cells mL^{-1}.

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