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Long-term Variations of Trophic State and Phosphorus Loading in Lake Andong, Korea

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The variation of trophic state was measured in a reservoir (Lake Andong, Korea) from 1993 to 2000. Phosphorus loading from the watershed was estimated by measuring total phosphorus concentration in the main inflowing stream (the Nakdong River). Phosphorus discharge from the pen-type fish farms was estimated from the amount of fish feed and the rate of phosphorus excretion per feed weight. The transparency in summer was about 2.0 m in 1993 and 1994, but it decreased to about 1.2 m in 1997 and 1998, and recovered to about 2.3 m in 1999 and 2000. TP increased from 11-30 mgP/m^3 in 1993 to 18-42 mgP/m^3 in 1998, but recovered to 8-13 mgP/m^3 in 2000, whereas TN decreased slightly from 1.81-2.96 mgN/L in 1993 to 1.17-1.80 mgN/L in 2000. TN/TP ratios decreased from 82-281 in 1993 to 21-143 in 1998, but again increased to 101-209 in 2000 due to the decrease of TP. The average chlorophyll-*a* concentration in growing season was in the range of 4.8-16.2 mg/m^3 from 1993 to 1997, but it decreased to 3.7-5.2 mg/m^3 after 1998. Trophic State Index had shown a gradual increase until 1996, and since then it has declined. The major cause of the trophic state recovery is thought to be the removal of fish farms in April 1998.

Key words : Lake Andong, trophic state, phosphorus loading, fish farm.

INTRODUCTION

Water quality problem in Korean lakes received much attention in 1990s. In general water quality deterioration is attributed to the excessive input of nutrients mostly from non-point sources like forests, livestock, agricultural runoff, and fish farms. In East Asian Monsoon region the inputs of nutrients from the watershed during the rainy seasons are much higher than those of dry seasons. Total phosphorus concentrations which are the major factor that controls eutrophication of lakes (Schindler and Fee, 1974; Bloesch *et al*., 1977) have been used for the estimation of trophic state, and biomass prediction of phytoplankton (Stauffer, 1985). Phosphorus loading during the rainy season in large artificial lakes in Korea were 70-80% of the total loading (Heo *et al*., 1992; Lee *et al*., 1993; Kim *et al*., 1997; Heo *et al*, 1998).

Watershed of Lake Andong includes two cities (Taebaek and Andong) and three counties (Bonghwa, Yeongyang and Uljin). Agriculture and small-scale livestock farming are the main economic activity in the watershed of Lake Andong. Many coal mines were active during the past decade in Taebak and Bonghwa area, but now they are almost abandoned. Currently, only four coal mines are in operation. The Sukpo refinery was a major factory, which produces zinc and sulfate, in the upper watershed. In the 1980s, many aqua cultures were started in most of the lakes of Korea and it reached its peak in the mid of 1990s.

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But since then, their sizes and number have decreased due to the removal and closures by the government and local agencies. In many artificial lakes in Korea, the phosphorus loadings from fish farms were estimated to exceed the loading from the watershed (Kim *et al.*, 1993).

Lake Andong, a warm monomicitic lake, is located in the upper Nakdong River with surface area of 51.5 km^2. The average water volume in the reservoir is 587×10^6 m^3 with a yearly average water inflow of 827.3×10^6 m^3. The mean depth is about 19.4 m, and the mean width is 1.2 km. The length of main axis is 43.5 km, and the hydraulic retention time is 1.33 yr. It has a total drainage area of 1,584 km^2. Total population in the watershed is 96,396 persons. The urban area in drainage basin is 142 km^2; and the paddy and dry field area is 256 km^2. The ratio of drainage area to lake area is 3 : 1. The annual precipitation rate is 1,076 mm/yr. BOD, SS, TN and TP loading from the watershed were estimated to be 16,211, 20,822, 3,256 and 642 kg/day, respectively (KOWACO, 1996). Lake Andong has many facets of function. It not only supplies water to Andong city and nearby regions, but also contribute to maintaining adequate water level and reducing water pollution of the Nakdong River in dry seasons. Although, Lake Andong is a very important part of the Nakdong River system, few research has been performed in this lake.

In this study, trophic state parameters were surveyed in Lake Andong. Turbidity, Secchi disc transparency (SD), phosphorus, nitrogen and chlorophyll-*a* concentration were measured at dam site from 1993 to 2000. Phosphorus loading from the watershed was estimated by measuring total phosphorus concentration in the main inflowing stream. The main objective of this study was to assess long term change of trophic state and the relationship with the change of fish farms.

MATERIALS AND METHODS

The water samples were collected at the dam site and the inflowing stream, on a monthly basis, through out July 1993 to December 2000, by using PVC Van Dorn sampler at different depths of 0-45 m as well as at the bottom layer (Fig 1). Samples collected were filtered with GF/C filter papers in the lab. The filter papers were kept frozen, and homogenized at the time of chlorophyll-*a* analysis. Lorenzen (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 was determined by cadmium reduction method after persulfate digestion, using flow injection autoanlyzer (BRAN+LUEBBE, Auto Analyzer3). Temperature and turbidity was measured with a multiprobe meter (YSI, 6000). Trophic State Index (TSI) was calculated according to Carlson (1977).

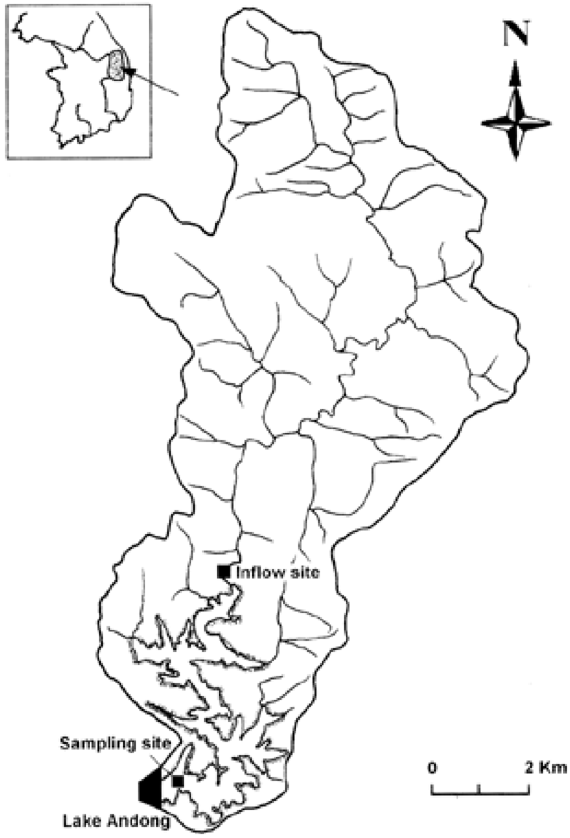

Fig. 1. Map showing the watershed and sampling sites.

RESULTS AND DISCUSSION

Ecosystem of Lake Andong had been adversely affected by the excess discharge of phosphorus from the watershed and floating pen-type fish farms. Total area of fish farm pens was 55,555 m^2 in 1996 (KOWACO, 1996). However, all fish farms were removed by April 1998. Phosphorus concentration was usually low in the Nakdong River, because heavily-vegetated forests (area 1,325 km^2) occupy the watershed and has moderate topsoil erosion. But high phosphorus concentration was observed in rainy seasons, from July to September every year.

The monthly average of precipitation rate, inflow rate, and the water level of Lake Andong were also taken into account as an important hydrological parameter (Fig 2). High inflow rate of 1,633 m^3/s and 1,720 m^3/s were observed in 3rd August and 24th September, 1999, respectively. The highest monthly average inflow of 200 m^3/s was observed in September, 1999. The monthly average rainfall was about 92 mm, with yearly average of 1,100 mm. In March 1995, the surface elevation reached its lowest level of 130 m, and the highest water level was recorded in September 1998 with the elevation of 160 m. The water level fluctuation range was of about 30 m throughout the period of study.

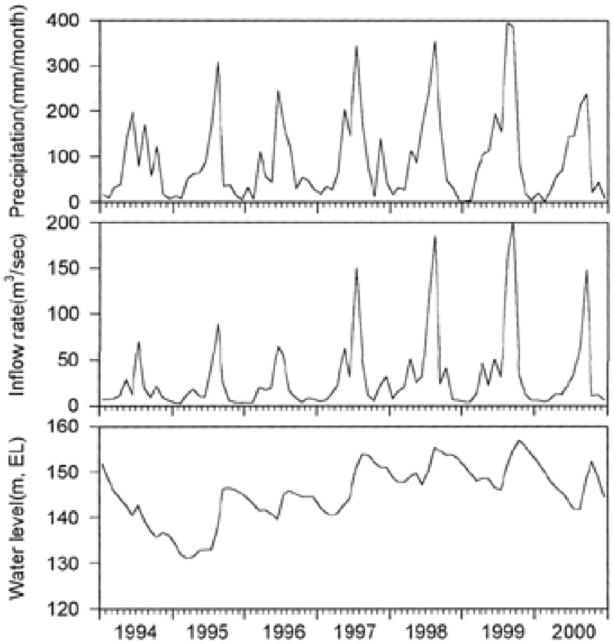

Fig. 2. The monthly variations of precipitation, inflow rate and water level.

Highest turbidity was 45.7 NTU in the intermediate layers in August 1998 (Fig. 3). Turbid water contained more phosphorus than clear water, both in dissolved and particulate form. In Lake Soyang, storm runoff flowed into the metalimnioin, and resulted in the increase of nutrient concentration in the epilimnion during autumn turnover (Heo *et al*., 1998). Tanaka and Tsuda's (1996) reported that in Lake Biwa, Japan, the turbidity in the intermediate layer increased to its peak in August and September in 1993 after three typhoons passed during that period.

The turbidity, TN, TP and TN/TP weight ratio were measured and their averages were calculated from the surface to 5 m depths, so that the impact on the lake ecosystem could be assessed. Higher turbidity was observed in August 1996 (6.8 NTU) and July 1997 (15.6 NTU), respectively. The average TP concentration in growing sea-

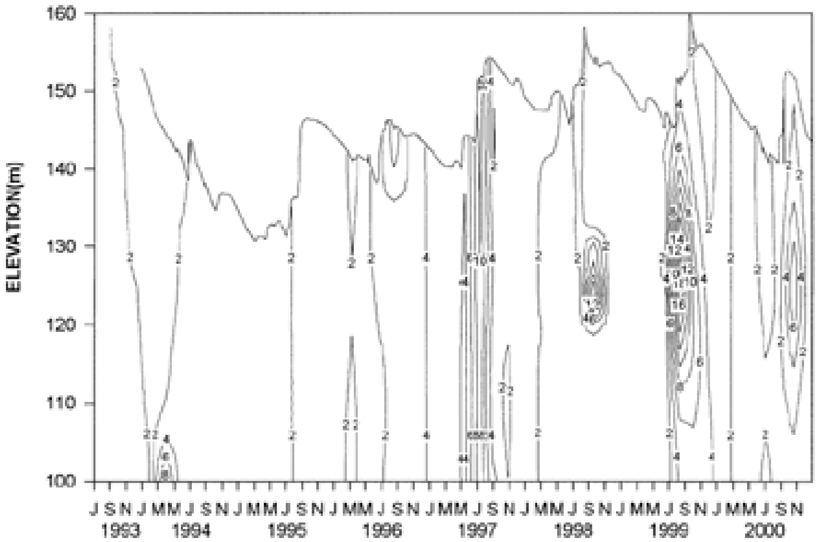

Fig. 3. The isopleths of turbidity (NTU) in Lake Andong.

sons (from May to October) increased from 18.2 mgP/m³ in 1993 to 31.0 mgP/m³ in 1998, but decreased to 17.8 mgP/m³ in 1999 and further down to 11.0 mgP/m³ in 2000. According to the lake classification based on the TP (Forsberg and Ryding, 1980), trophic state in Lake Andong can be classified as mesotrophic (15−25 mgP/m³) to eutrophic ($>$25 mgP/m³) and again back to oligotrophic ($<$15 mgP/m³) according to the change of TP. The average TN concentration in growing season was in the range of 2.28−2.67 mgN/L until 1997, without much yearly variation, but decreased to 1.80−1.37 mgN/L during 1998 to 2000. TN/TP weight ratio decreased from 82−281 in 1993 to 21−143 in 1998, but again increased to 101−209 in 2000 due to the decrease of TP (Fig 4). Most of the lakes in Korea have been reported to have an average TN/TP weight ratio in the range of 40−160 (Kim *et al.*, 1997).

DIP and nitrate−nitrogen concentration of the epilimnion were in the range of 0.3−15.1 mgP/m³ and 0.8−2.1 mgN/L, respectively from 1993−2000. The DIP showed some fluctuations, but total phosphorus concentration exhibited less variation. The DIP in the epilimnion, which is utilized by algae, bacteria and macrophytes for their growth, sometimes exhibited a decline during algal blooms. The nitrate−nitrogen concentration showed a slight gradual decrease throughout the study period. The nitrate−nitrogen yearly average concentration was about 1.5 mgN/L. It was higher than that in Lake Soyang that has similar watershed characteristic with Lake Andong, where the yearly average concentration of nitrate was about 0.6 mgN/L (Heo and Kim, 1997).

The average chlorophyll−*a* concentration in growing season was in the range of 4.8−16.2 mg/m³ from 1993 to 1997, but it decreased to 3.7−5.2 mg/m³ after 1998. Higher chlorophyll−*a* concen-

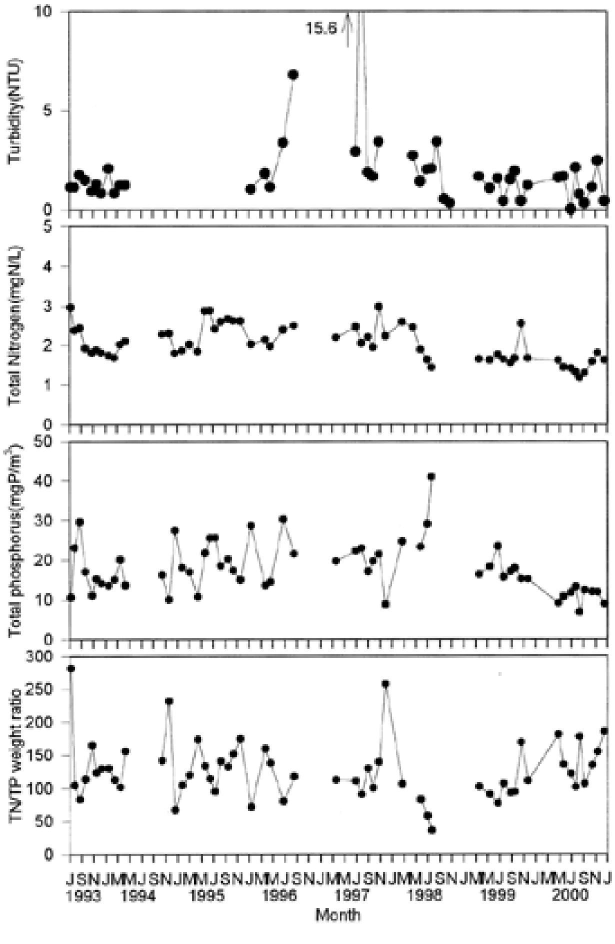

Fig. 4. The monthly variations of total nitrogen (TN), total phosphorus (TP) and TN/TP weight ratio in Lake Andong (average of 0, 2, 5m).

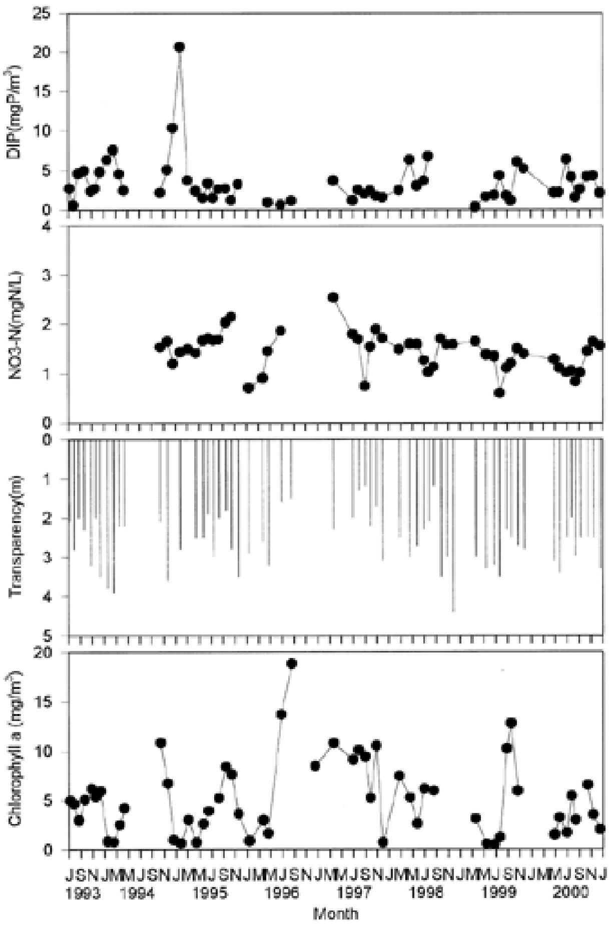

Fig. 5. The monthly variations of DIP, NO_3−N, SD and chlorophyll−*a* concentration (average of 0, 2, 5 m)

trations were observed in the period, which coincided with the high turbidity. Lake Okjong has an average chlorophyll-*a* of 2.4−18.7 mg/m^3 (Kim *et al*., 1997). According to the US EPA (1976) guidelines for lake classification on the basis of chlorophyll-*a* Lake Andong was eutrophic ($>$10 mg/m^3) in 1994, 1996 and 1997, but it became an oligotrophic ($<$5 mg/m^3) lake after 1998.

Minimum Secchi disc transparency in summer was about 2.0 m in 1993, but it decreased to about 1.2 m in 1997 and 1998 due to water blooms, but recovered to about 2.3 m in 1999 and 2000. The average Secchi disc transparency in growing season decreased from 2.5 m in 1993 to 1.7 m in 1997, but recovered to 2.5−2.9 m in 1998 to 2000 (Fig. 5). The increase in Secchi disc depth is thought to be due to the removal of fish farms and reduced nutrients loading from fish farms, which resulted in reduced phytoplankton biomass. In Lake Soyang, water blooms caused Secchi disc depth to decrease to less than 2 m (Heo, 1993). Secchi disc depth range of lake Andong was in the similar range as in other lakes, such as 1.4−4.0 m Lake Okjong (Kim *et al*., 1997), 1.5−4.0 m Lake Hapchon (Kim *et al*., 1998) and 0.8−3.5 m Lake Jinyang (Kim *et al*., 1999).

TP during the winter turnover was 20 mgP/m^3 throughout the lake from 1994 to 1999, but it decreased to 10 mgP/m^3 in 2000, which can be attributed to the removal of fish farms. The hypolimnion showed higher concentrations after the winter turnover than other seasons. The highest concentration was recorded as 55.7 mgP/m^3 in August 1999 and in October 1999. Also TP was higher (36−217 mgP/m^3) in the metalimnion (Fig. 6). TP and DIP increased in the intermediate layer following rainfall. Turbidity was higher in the intermediate layers in the August 1999 just after heavy rain event, but the turbidity decreased in October 1999, which may be due to the settlement of the particulate matters and discharge of turbid intermediate layer through the dam outlet.

DIP concentration showed a similar trend to TP. DIP concentration during the winter turnover was about 4 mgP/m^3 (Fig. 7). The TN during winter turnover was in the range of 1.6−2.0 mgN/L. The TN in the epilimnion ws in the range of 1.4−3.9 mgN/L (Fig. 8). TN did not show significant correlation with the inflow rate.

The yearly averages of TSI (Chl), TSI (TP), and TDI (SD) were calculated only for the growing seasons (May−October) to assess the change of trophic state. The TSI showed a gradual increase till 1996 and began to decline since then, which can be attributed to the decline of phophorus loading that started in 1997 May by the gradual removal of fish farms (KOWACO, 1996). The TSI was 53 in 1993 and 49 in 2000. Changes of TSI in Lake Andong also proved that it was on the process of recovery (Table 1).

The relationship of the inflow rate (Q) of the Nakdong River vs. TP showed a positive correlation with a coefficient (R^2) of 0.54 (Fig. 9). The

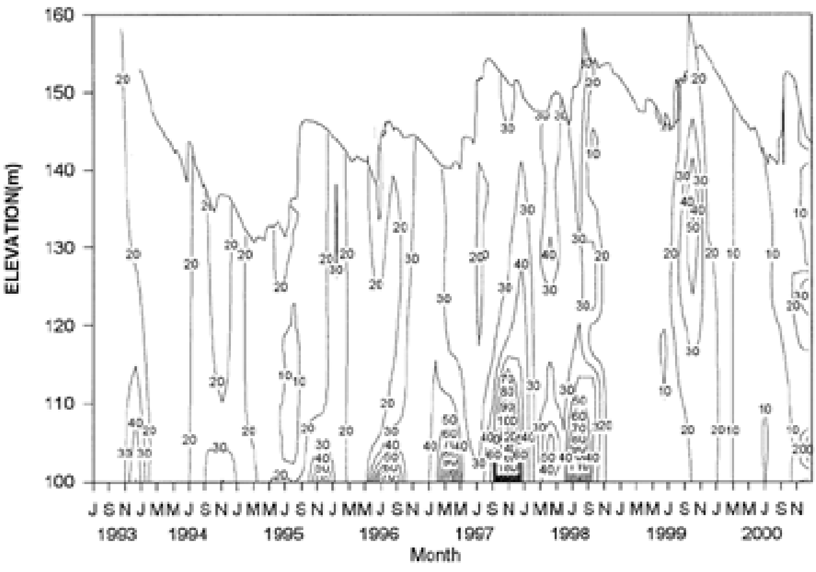

Fig. 6. The isopleths of total phosphorus concentration (mgP/m^3) in Lake Andong.

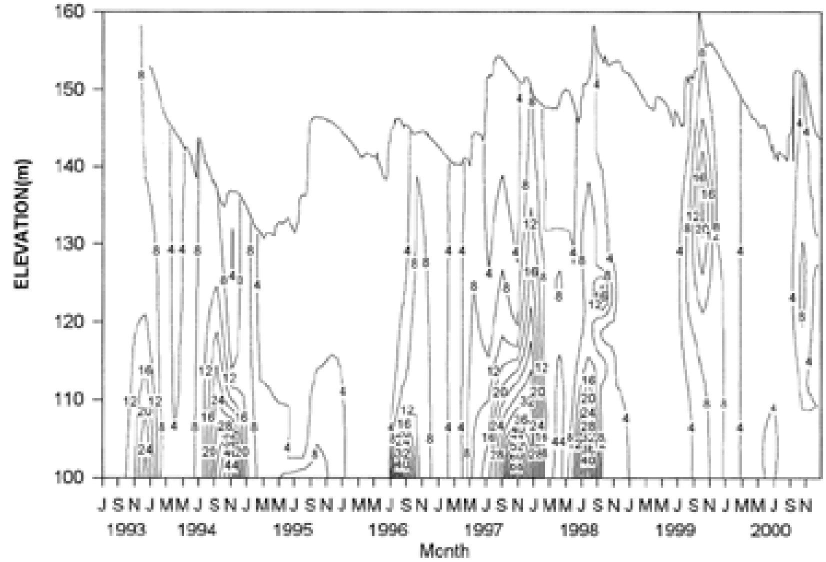

Fig. 7. The isopleths of dissolved inorganic phosphorus concentration (mgP/m^3) in Lake Andong.

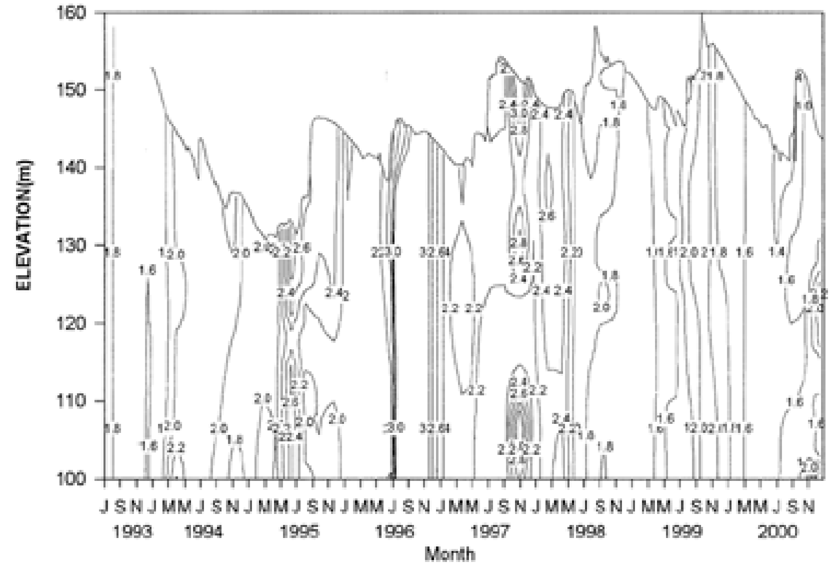

Fig. 8. The isopleths of TN concentration (mgN/L) in Lake Andong.

empirical relationship, $TP = 2.38Q^{0.61}$, was developed by the continuous monitoring of inflow rate and plotting the values of TP with respect to it. Therefore, TP could be predicted with the above equation as a function of inflow rate, which was highly valid and reliable in this study ($r^2 = 0.54$, $p < 0.001$, $n = 123$).

The average TP loading from the watershed was estimated to be 64 tP/yr. The TP loading from the watershed in 1994, 1995, 1996, 1997, 1998, 1999 and 2000 were 28.9, 29.6, 20.7, 64.9, 93.4, 153.1 and 60.1 tP/year respectively. The high TP loading in 1999 was due to the highest inflow rate in September 1999. TP loading in the rainy season, July to September was about 70% of total annual phosphorus loading. It was reported that the first flush in the first rain event contributed the largest proportion to annual TP loading of the rainy season in Lake Dalbang, while other subsequent rainfalls did not show high nu-

Table 1. Trophic state indices (TSI) of Lake Andong. TSI was calculated from the average of warm season (May-October).

Year	TSI (chl *a*)	TSI (TP)	TSI (SD)
1993	55	46	47
1994	63	44	49
1995	56	48	48
1996	67	51	54
1997	61	48	53
1998	52	54	47
1999	56	46	45
2000	53	39	46

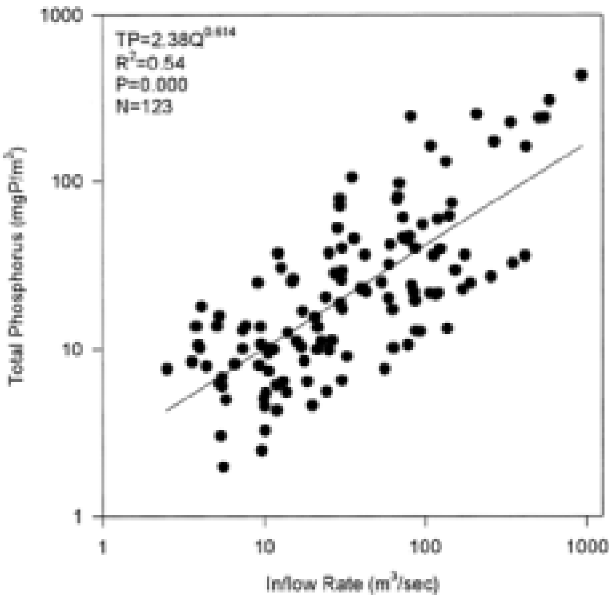

Fig. 9. Plot of inflow rate vs. total phosphorus in the inflowing water, the Nakdong River.

trient concentration. Heo *et al.* (1999) reported Phosphorus discharge of fish farm was estimated from the amount of fish feed applied annually and the unit rate of phosphorus excretion per feed weight (Kim *et al.*, 1993). The phosphorus loading from the fish farms was 56 tP/yr. With the removal of fish farms in April 1998, the lake is becoming oligotrophic, and the trophic state is on the gradual process of recovery.

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<국문적요>

안동호의 장기간의 영양상태와 인부하량

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안동호에서 1993년부터 2000년까지 영양상태와 인부하량의 장기적인 변화를 조사하였다. 조사항목은 탁도, 수온, 투명도, 인, 질소 및 엽록소 *a* 농도 등이며, 댐 앞지점에서 월 1회 조사하였다. 유역으로부터의 인부하량은 주 유입수에서 주 1회 혹은 우기시 수시로 조사된 자료와 유입수량으로부터 산출하였다. 양어장으로부터의 인부하량은 사료공급량과 원단위로부터 산출하였다. 여름에 최소 투명도 값이 1993년과 1994년에는 약 2 m 정도이었으나, 1998년에는 약 1 m를 보였다. 표층의 총인 농도는 1993년에 11-30 mgP/m^3에서 1998년에는 18-42 mgP/m^3으로 약간 증가하였다. 그러나 2000년에는 8-13 mgP/m^3으로 회복되었다. 표층의 총질소는 1993년에 1.81-2.96 mgN/L에서 2000년에는 1.17-1.80 mgN/L로 약간 감소하였다. TN/TP 비는 1993년에 82-281이었으나 1998년에는 21-143로 감소하였다. 그러나 2000년에는 TP의 감소에 따라 101-209로 다시 증가하였다. 여름에 엽록소 *a* 농도는 1993년부터 1997년까지 4.8-16.2 mg/m^3의 범위를 보였으나 1998년 이후에는 3.7-5.2 mg/m^3으로 다소 감소되었다. 안동호의 영양상태는 1996년까지 점차적으로 증가되어왔으나 그 이후 감소되고 있는 것으로 나타났다. 영양상태 회복의 주요 요인은 1998년 4월에 양어장의 철거에 따른 것으로 판단된다.