Korean J. Limnol. 38 (Special issue): 44~53 (2005)

Prolonged Turbidity of the Lower Nakdong River in 2003

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The Nakdong River, which lies in a monsoon climate zone with warm rainy summers and cold dry winters, is a typical ecosystem showing the attributes of a regulated river. In 2003, the total annual rainfall (1,805 mm) was higher than the average of the past nine years from 1994 to 2002 (1,250 mm). In September a powerful typhoon, Maemi, caused a big impact on the limnology of the river for over two months. Among the limnological variables, turbidity in 2003 (37.4±94.1 NTU, n = 54) was higher than the annual average for ten years (18.5±2.3 NTU, n = 486) in the lower part of the river (Mulgum: RK 28). Furthermore, physical disturbance (e.g. stream bank erosion within channel) in the upstream of the Imha Dam (RK ca. 350; river distance in kilometer from the estuary barrage) in the upper part of the river was a source of high turbidity, and impacted on the limnological dynamics along a 350 km section of the middle to lower part of the river. After the typhoon, high turbidity persisted more than two months in the late autumn from September to November in 2003. Flow regulation and the extended duration of turbid water are superimposed on the template of existing main channel hydroecology, which may cause spatial changes in the population dynamics of plankton in the river.

Key words : Nakdong River, typhoon 'Maemi', turbidity, population dynamics, plankton

INTRODUCTION

Regulated rivers are often compromised by a lack of data on the pre-impoundment conditions, benthic variables and spatial changes in water quality (Allen and Flecker, 1993). In a river, the flow regime is probably one of the most important factors associated with plankton dynamics and water quality. Furthermore, turbidity is one of the significant physical factors that can have an effect on the biological dynamics of the river ecosystem. The presence of suspended solids or sediments in the river can have both a direct effect on aquatic life through damage to organisms and their habitats and an indirect effect through their influence on turbidity and light penetration (Flemer, 1970; Cloern, 1987; Cole *et al.*, 1992). High mineral turbidity may occur in rivers, particularly during periods of high flow, resulting in the reduction of the food availability for zooplankton and of phytoplankton by light limitation (Shiel and Walker, 1984). Abrupt increases of turbidity and of the concentration of suspended solids are able to cause the change or disappearance of submerged plants in the river (Koerner, 2001; Lee and Kang, 2001; Horpplila and Nurminen, 2003).

Increased turbidity has been shown to have a variety of influences on biota through the changes

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in ecological characteristics, the availability of resources, and species interactions (Hart, 1990). In general, high turbidity in the river ecosystem emerges primarily from two major causes. One is due to an increased flow of the waterbody through rainfall, discharge and snowmelt. It is known that suspended solids are often a prominent feature of tropical rivers although their role is poorly understood (Payne, 1986), while the suspended solids are sometimes caused for a short time by excessive snowmelt in Tundra areas (Walker *et al.*, 2003). The other is due to an increase of algal biomass (Ceballos *et al.*, 1998; Ha *et al.*, 1998; Muylaert and Sabbe, 1999; Porat *et al.*, 1999).

Turbid water has emerged as an important environmental issue for the uses and management of water resources in Korea (Shin and Hwang, 2004). Many researches on the impact of turbidity have been conducted with respect to large reservoirs (Heo *et al.*, 1998; Shin *et al.*, 2003). The occurrence of turbid water is frequently one of the anthropogenic effects derived from intense watershed uses and various constructions. The causes of turbid water in Korea are mainly related to active soil erosion and wash−out of the land surface by heavy rainfall (Shin *et al.*, 2004). However, enough surveys and investigations concerning downstream transport in the river systems have been not performed. Since the catchment area of the river is larger than those of lakes or reservoirs, turbidity research in the rivers, should consider spatial patterns along the main channel and tributaries.

Seasonal changes of the limnological traits are relatively well documented in the lower Nakdong River (Kim *et al.*, 1998; Ha *et al.*, 2002). During the summer period, the duration and amount of rainfall can influence turbidity. Increased turbidity due to a sudden increase of discharge caused by the monsoon or typhoons can usually last one to two weeks (Park, 1998). In contrast, algal development can also cause high turbidity for several weeks, and high turbidity and low light penetration through the summer bluegreen algal bloom were frequently observed (Ha *et al.*, 1998).

Our objective was to evaluate variability in discharge and limno−ecological variables in relation to turbidity in the river before, during, and after the powerful typhoon 'Maemi' in September 2003 passed through the middle part of the Nakdong River watershed. In this study, we compared the limnology of the lower Nakdong River in the year 2003 with the past nine years and reported the feature of prolonged high turbidity in autumn 2003. In order to identify the source of turbidity, we surveyed the longitudinal patterns of turbidity along the main channel of the river.

THE DESCRIPTION OF STUDY SITES

Nakdong River is one of the largest river systems in South Korea (Fig. 1). At present, almost ten million people depend on the river for drinking, industrial and irrigation water resources. The flow in the Nakdong River is regulated by four multi−purpose dams and an estuarine barrage. However, due to the construction of these facilities, the retention time of the river increased and the water quality of the river has deteriorated. The eutrophication of the river has been

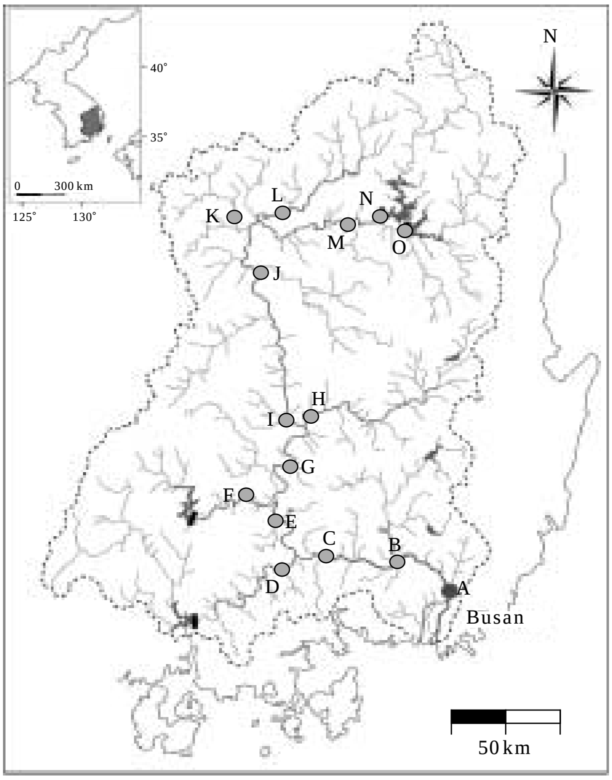


Fig. 1. Study sites in the Nakdong River basin (A: Mulgum, B: Hanam, C: Namji, D: Nam River, E: Jeokpo, F: Hwang River, G: Goryoung, H: Gumho River, I: Waegwan, J: Sangju, K: Young River, L: Naeseong Stream, M: Poongchon, N: Andong dam, O: Imha dam).

accelerated since 1990 and accompanies recurrent algal blooms (Joo *et al*., 1997).

In the Nakdong River basin, heavy rainfall like monsoon occurs for about a half month from late June to mid July. In the late summer or the early autumn several typhoons may influence the river system with heavy rain and large discharge (Park, 1998). Physical changes caused by these events can cause a profound impact on the plankton dynamics and general limnology in summer and the early autumn (Kim *et al*., 1998). As a dry season begins from the late October or the early November, winter diatom species (e.g. *Stephanodiscus hantzschii*) tend to rapidly proliferate. During this dry season, amount of rainfall is very small and the lower part of the river becomes a river-reservoir hybrid type (Kim and Joo, 2000).

MATERIALS AND METHODS

Limnological samplings have been conducted weekly in the lower Nakdong River, Mulgum (River Kilometer, RK 28; RK 0: Nakdong River Estuarine Barrage), since 1993. In addition, surveys at eight more sites along the main channel and tributaries of the river were implemented biweekly between Waegwan (RK 178) and Hanam (RK 60) (Fig. 1). Besides, the two additional investigations on October 31 and November 13 in 2003 (additional sampling sites: Andong Dam (RK 352), Imha Dam (RK 355), Poongchon (RK 309), Sangju (RK 261), Naeseong Stream (RK 311), Young River (RK 296)) were conducted in order to determine the source of turbidity in the upper part of the river (Andong Multi-purpose Dam: RK 352 and Imha Multi-purpose Dam: RK 355) (Fig. 1).

The dynamics of the physical and chemical parameters (e.g. rainfall, turbidity, discharge, water temperature, dissolved oxygen, total nitrogen, total phosphorus and chlorophyll *a*) were examined using dataset during 1994-2003. Precipitation (e.g. an average value in five sites which are Andong, Daegu, Miryang, Hapchon and Jinju) and discharge in Samlangjin were obtained from the Nakdong River Flood Control Center. Physico-chemical data such as water temperature (YSI, model 55), turbidity (HF scientific Inc., model 20012), Secchi disc depth, DO (YSI, model 55), pH (Orion, model 250A), conductivity (YSI, model 30) and alkalinity were measured. Biological data such as chlorophyll *a* were measured using extraction methods described by Wetzel and Likens (1991).

We divided rainfall patterns for the past ten years into three climatic classes in order to compare rainfall in 2003. Mean ± Standard Deviation (S.D.) was used for a criterion of the classification (Zar, 1984). Dry and wet years were defined out of ranges of mean ± S.D.

RESULTS

1. Limnological dynamics

There were distinct inter-annual variations of precipitation and limnological variables in the lower part of the river (Figs. 2 and 3). In the Nakdong River basin, annual precipitation for the past ten years averaged was 1250 ± 310 mm, and 2003 was the highest precipitation year (1805 mm) (Fig. 2). The amount of rainfall was related to discharge and turbidity, which have cascade-impacts on water temperature, dissolved oxygen and the concentration of chlorophyll *a*. The average annual water temperature was 17 ± 8.7°C, while it showed the lowest value (15.4°C) in 2003. The summer maximum water temperature in rainy years (i.e. 1998, 1999, 2002 and 2003) was much lower than in dry years. Chlorophyll *a* showed an average value of 42.5 ± 81 μg L^{-1} for ten years. Chlorophyll *a* mostly fluctuated along the patterns of precipitation and discharge, and the variation was also relatively

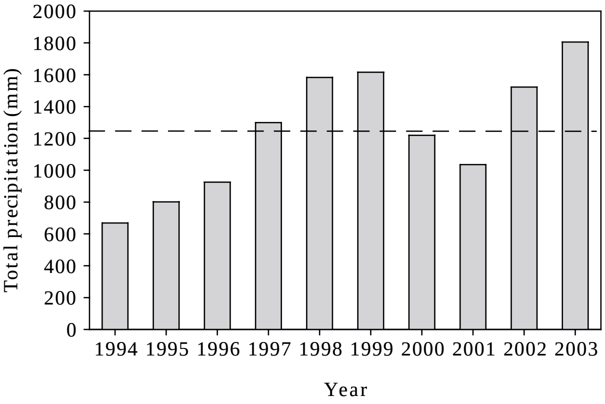


Fig. 2. Total amount of precipitation from 1994 to 2003 (Average of Andong, Daegu, Hapchon, Jinju and Miryang; Dash line: average precipitation for ten years, 1250 mm).

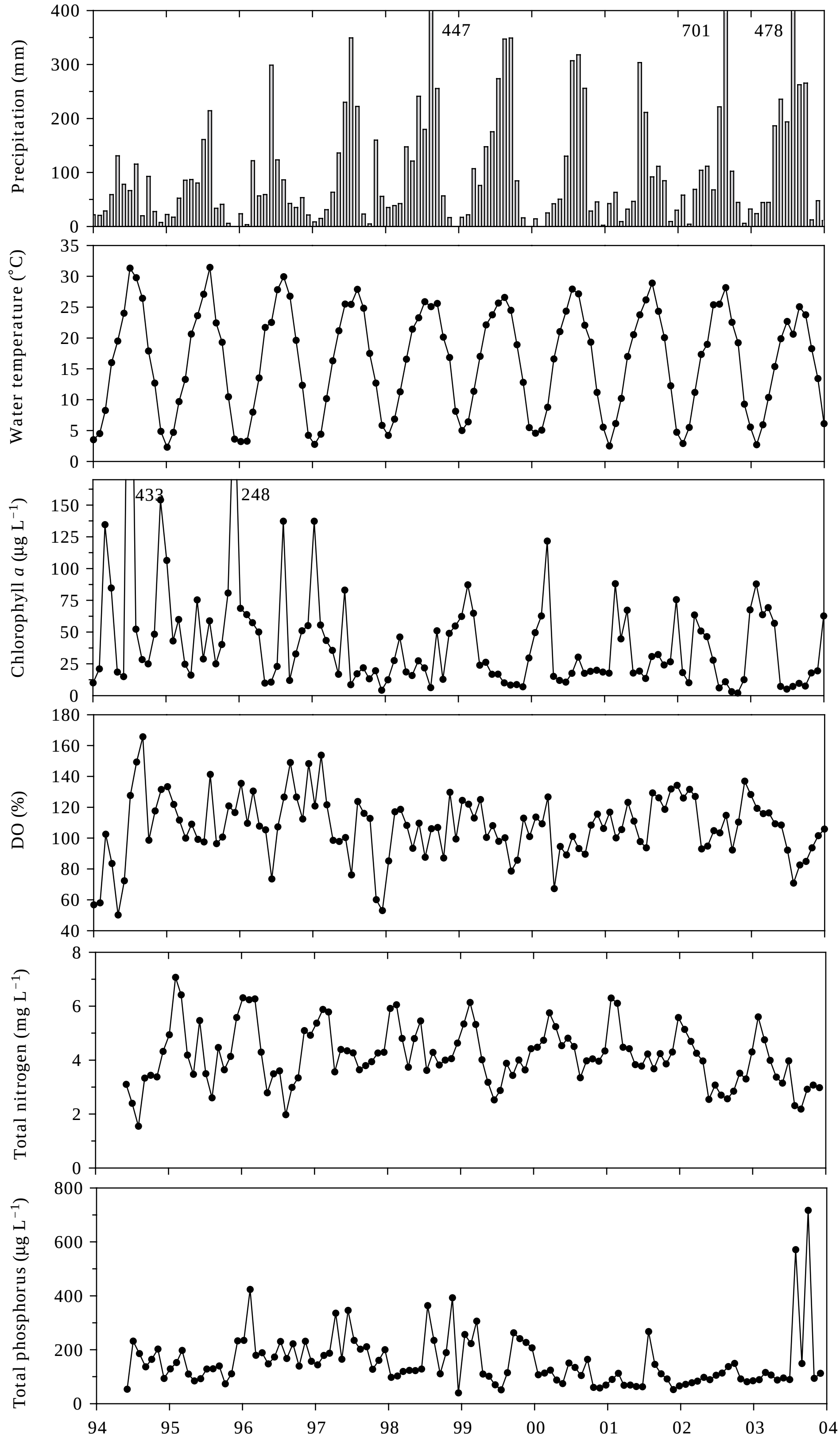
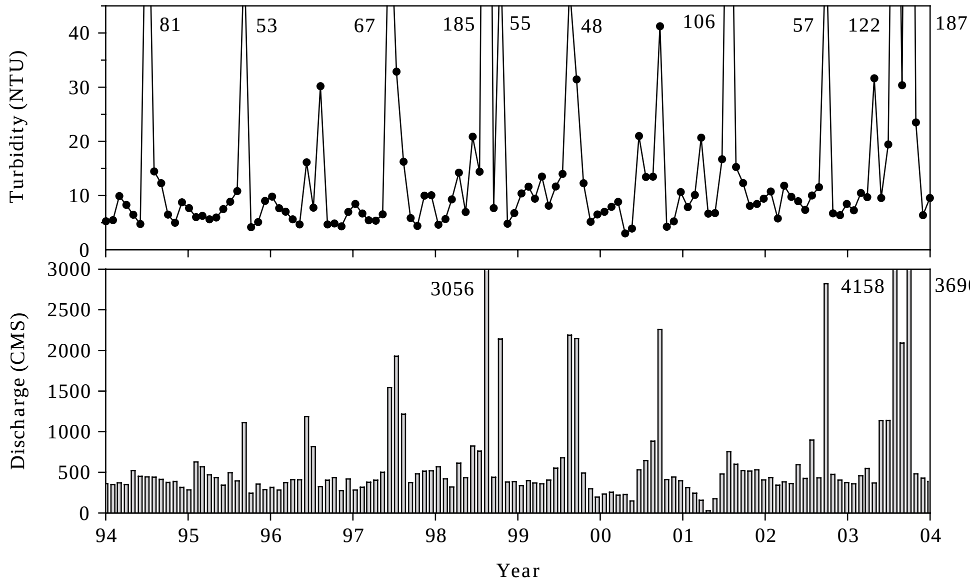


Fig. 3. Limological characteristics in the lower Nakdong River (Mulgum, 1994～2003).



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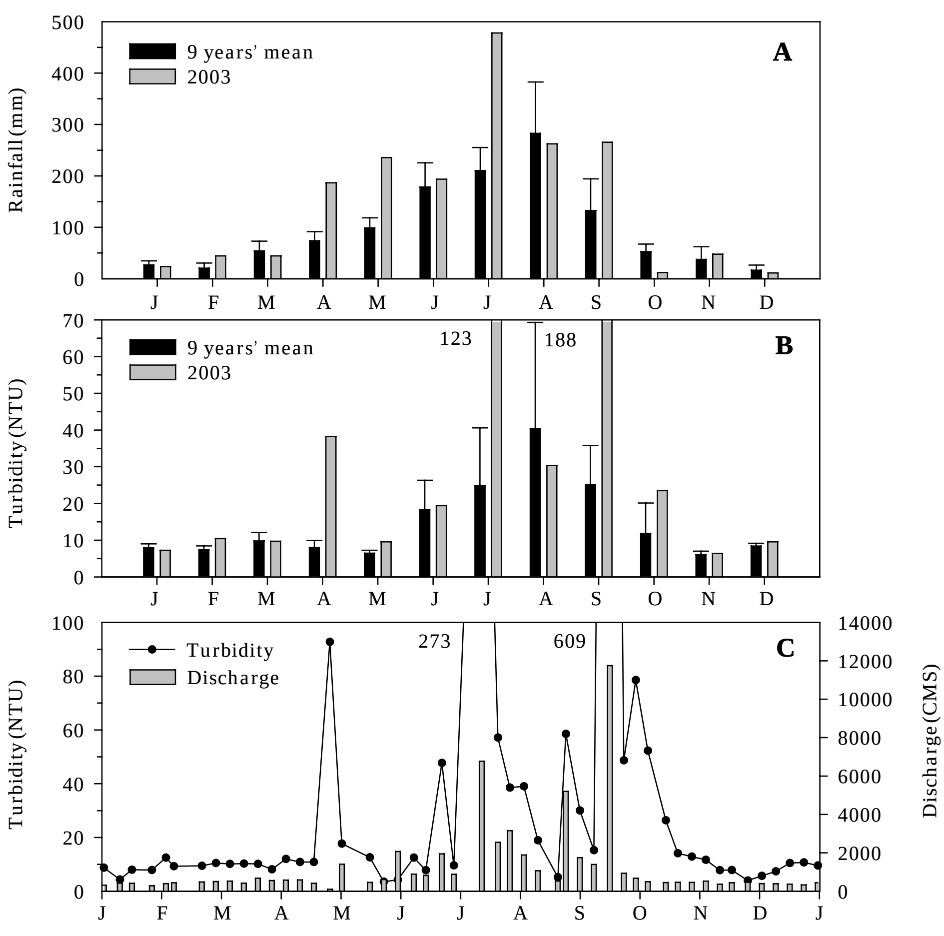

Fig. 4. Comparison of rainfall and turbidity in the lower Nakdong River (Mulgum, 1994∼2003, A: Rainfall of 2003 and the mean of 9 years, B: Turbidity of 2003 and the mean of 9 years, C: Turbidity and discharge in 2003).

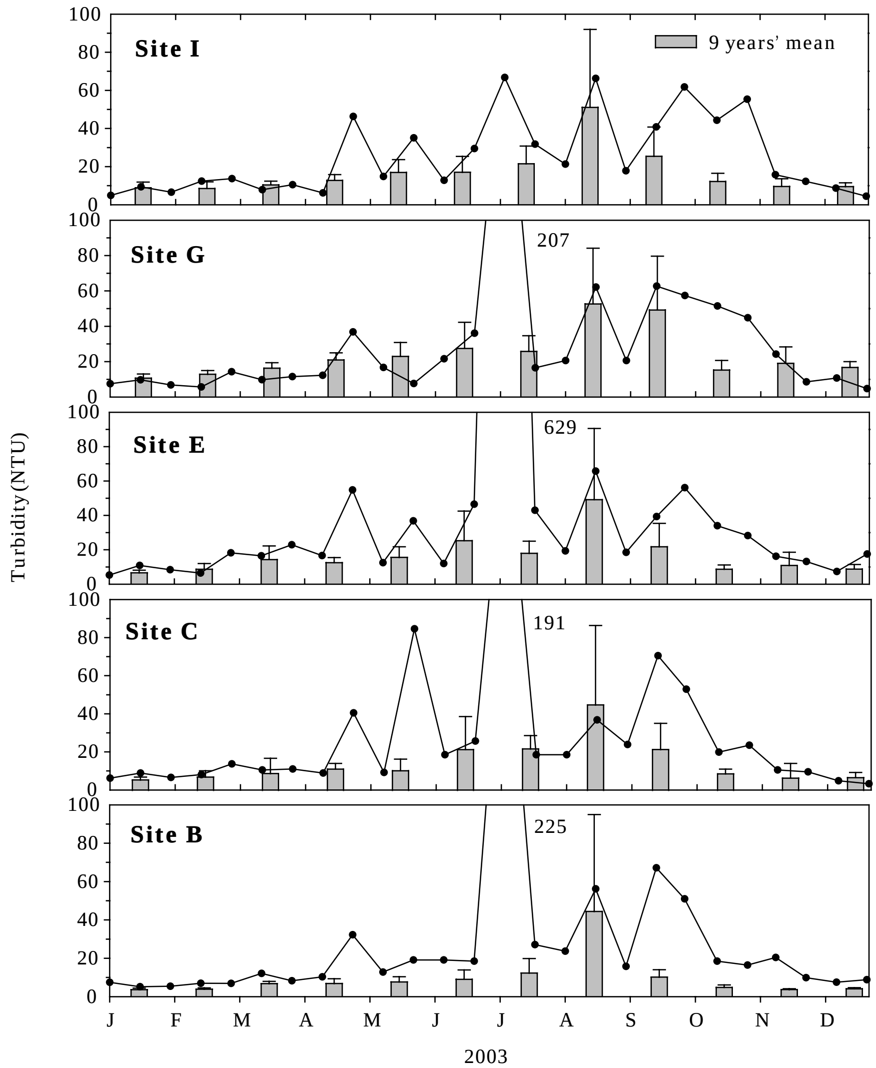

Fig. 5. Longitudinal pattern of turbidity in the main channel of the Nakdong River (nine years: 1994～2002, B: Hanam, C: Namji, E: Jeokpo, G: Goryoung, I: Waegwan).

small in rainy years. After the summer of 2003, chlorophyll *a* was low until November due to the high turbidity and high discharge. Exceptionally high chlorophyll *a* concentrations in 1994 (433 μg L^{-1}) and 1995 (248 μg L^{-1}) resulted from algal blooms and small precipitation and discharge in the summer. Especially in 1994, the high saturation of dissolved oxygen (166%) and high turbidity (81 NTU) during the summer, were caused by blue-green algal bloom. With respect to nutrient concentration, the total nitrogen (TN) and total phosphorus (TP) did present the distinct variability of annual patterns (Fig. 3). One of the most dramatic inter-annual changes was observed in the total phosphorus (TP). The fluctuation of total phosphorus (TP) that varied between about 50 μg L^{-1} and 400 μg L^{-1} from 1994 to 2002, increased up to 700 μg L^{-1} together with the high turbidity in 2003 (Fig. 3).

In the case of turbidity (18.5 ± 2.3 NTU), the highest value was also observed in 2003 (37.4 ± 94.1 NTU). High turbidities were observed in every year through algal blooms or heavy rainfall. However, the prolonged high turbidity had meteorological and hydrological impacts in autumn 2003. Linear correlation between discharge and turbidity in the lower Nakdong River for the ten years was not so high (r = 0.76, n = 505), while correlation in wet years (i.e. 1998, 1999, 2002 and 2003) showed a high value (r = 0.81, n = 155). Particularly in the case of year 2003, the correlation value was the highest (r = 0.91, n = 47).

2. Prolonged turbidity in 2003

Overall rainfall was very high in the Nakdong River catchment area in 2003 (Fig. 2). The amount of rain in April and May of the year 2003 was larger than nine years average monthly rainfall, and was reflected in the increase of turbidity (Fig. 4). High rainfall in July indirectly indicates the duration and scale of monsoon-like weathers, which is a monsoon event in the Korean peninsula. The large amount of rainfall in September 2003 was due to the occurrence of the typhoon 'Maemi'. Annually several typhoons affect Korea and Japan, normally from August to October. However, the typhoon 'Maemi' was not on an ordinary scale, and penetrated to the middle part of the Nakdong River catchment area. This typhoon was accompanied by heavy rainfall and 259 mm of rain fell within a day in the southwestern part of the basin. It took three days for the typhoon to pass the Nakdong River basin. Turbidity was highly correlated with precipitation and discharge. During the major rain events in summer, the increase of turbidity was observed in every year except the summer of 1994. However, the average turbidity in October 2003, was recorded as 23.4 NTU (at Mulgum) in spite of a reduction of discharge and precipitation. High turbidity was maintained until the end of October (Fig. 4).

3. Longitudinal patterns of turbidity

The high turbidities of the main channel (Hanam, Namji, Jeokpo, Goryoung and Waegwan; RK 60 to 178) have returned to normal levels since November 2003. However, the lower part of the river tended to recover from turbidity more quickly (Fig. 5). While Waegwan (RK 178) and Goryoung (RK 152) still exhibited high turbidities in late October, turbidities at Namji (RK 84) and Hanam (RK 60) were close to the average of the nine years. The prolonged high turbidity in the middle part of the river was caused by turbid inflow water from the upper part of the river, while it was thought that the low turbidity at the lower part of the river (RK 28 to 84) was due to settling and dilution from other tribu-

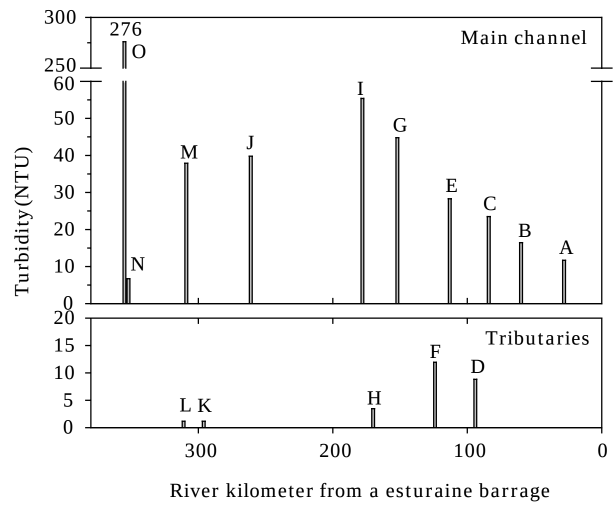

Fig. 6. Longitudinal pattern of turbidity after typhoon 'Maemi' (A: Mulgum, B: Hanam, C: Namji, D: Nam River, E: Jeokpo, F: Hwang River, G: Goryoung, H: Gumho River, I: Waegwan, J: Sangju, K: Young River, L: Naeseong Stream, M: Poongchon, N: Andong dam, O: Imha dam, measured on Oct. 31 2003).

taries.

The high turbidities persisted more than one and a half months after the typhoon 'Maemi' (Sep. to mid Oct. 2003). In the main channel, high turbidities were observed below the Imha Dam (Site O: 276 NTU, Site N: 6.7, Site M: 37.9, Site J; 39.8), and the turbidities of the major tributaries were normal (Site L: 1.1, Site K: 1.1, Site H: 3.4, Site F: 11.9, Site D: 8.8) (Fig. 6). In the main channel, several sites (Site G, Site I, Site J, Site M) located at about RK 150 to about RK 320 still displayed high turbidities in late October. An almost identical pattern of the longitudinal distribution of turbidities was observed in mid November (data not shown). Turbidities at the central part of the Imha Dam were 276 NTU on Oct. 31 and 310 NTU on Nov. 13 in 2003.

DISCUSSION

This study examined the patterns of spatial and year-to-year variations of turbidity along with hydro-and meteorological changes (e.g. precipitation and discharge) at the lower part of the river during the past ten years. Throughout the study, prolonged turbidity was due to the discharge of the turbid water from the Imha Dam between late October and early November. Both multi−purpose dams, Andong and Imha dams, are located in the same region, and they are geographically very close to each other (distance: 3 km). However, turbidities at the dams were extremely different (Fig. 6). Highly turbid water in the Imha Lake has been reported in many previous researches (Lee, 2003; Lee *et al.*, 2004). They reported that soil erosion and wash−out of the land surface and stream channel in the Imha Dam basin were primary causes of the high turbidity.

Discharge of the turbid water from Imha dam brought about the changes of limnological patterns. River inflows, closely related to the changes in temperature, the availability of nutrients and suspended solid load often create physical horizontal gradients in freshwater ecosystems (Hart, 1990; Thornton *et al.*, 1990). These variations in water characteristics may affect the distribution and occurrence of organisms in a system (Kim *et al.*, 2001). During the highly turbid period from October to late November, the phytoplankton biomass at the lower reach of the Nakdong River was significantly lower than nine−year average (Chl. *a*: 28 $\mu g\ L^{-1}$ (n = 48) in 2003, 43 $\mu g\ L^{-1}$ (n = 472) for nine years).

Compared with patterns of discharge and turbidity, the large amount of rainfall seems to be accompanied with a decrease in water temperature and inflow of phosphorus. In wet years (e.g. 1998, 1999, 2002 and 2003), peak water temperature in summer was lower than in normal and dry years. The relationship between turbidity and TP was reported in the previous researches (Grayson *et al.*, 1996). In general, an increase of phosphorus in lake or river ecosystems is a cause of algal growth (Harris, 1986). However, the occurrence of a powerful typhoon and its disturbance caused prolonged high turbidity. Discharge of the river dropped to normal levels after the typhoon, but high turbidity was extended until mid October in 2003 (Mulgum, RK 28). In this case, prolonged turbidity could inhibit algal growths because high turbidity could block photosynthesis in algae (Reynolds, 1984; Cabeçadas, 1998).

Turbidity in the late fall to early spring at the Nakdong River is relatively low (Kim *et al.*, 2003), and fluctuates with intermittent rain−events such as summer intensive rainfall and typhoons. Sudden increases in turbidities in summer are common (Park, 1998). After heavy rains in summer, increased turbidities in the lower part of the river are normally stabilized within one to two weeks (Kim and Joo, 2000). However, the high turbidity in October of 2003 was unexpected and unusual. Turbidities during this period were two times higher than those of the past nine years throughout five sites along the main channel (RK 28 to 178). The turbidity regime in the middle of the river and downstream was substantially altered by dam−related increased turbidity. The powerful typhoon, Maemi, disturbed the upper part of the river, and caused high turbidity in the dams. Firstly, soil erosion and bank erosion in the major tributaries of the Imha Dam was the source of the high level of suspended matter (KOWACO, 1994; Chon and Bae, 1999). Secondly, sediment disturbance could increase turbidity in the lake (Shin *et al.*, 2003). In the case of the Imha dam, complex combinations of exterior soil constituents and interior sediment disturbance could be involved in prolonged high turbidity.

The influence of gravel extraction in the middle part of the river was also considered through an investigation at the extraction sites. Turbidity caused by the extraction activity at Waegan (one below the extraction site, two above the site) did not show any significant change in November 2003. In this study, the analysis on the particles in water was not conducted. However, further studies on the constituents and sizes of particles could provide more information on a source of turbidity.

During the high turbidity period, the Nakdong River system which possesses multi−purpose dams and an estuarine barrage is morphologically different from general other river systems. In these types of rivers, big impacts or disturbances such as heavy rainfall and typhoons can cause high turbidity, and the disturbance of upper reaches can influence ecological aspects even in the lower parts of the river. The monsoon and typhoons are iterative events every year, but their disturbance effects can be significant in the river ecosystem depending on its spatial, temporal and physical features. The research regarding disturbance effects can provide promising information about the improvement of streams and banks. Further studies should address the detailed causes of high turbidity in the drainage basin of the Imha Dam as well as channel geomorphology and the soil constituents of the stream system. In addition, appropriate selective withdrawal in lakes and reservoirs should be implemented (Shin *et al*., 2004). Furthermore, the relationship between plankton dynamics and turbidity should be elucidated and understood in response to the above explanations. These research projects will be help to support the establishment of a long-term plan for total catchment management.

ACKNOWLEDGEMENT

The authors are thankful to the members of the Limnology Lab of Pusan National University for sampling assistance. This research was financially supported by the Ministry of Environment (Long Term Ecological Research 2004). This paper is contribution No. 44 of the Ecosystems Study on the Nakdong River of the Limnology Lab., PNU.

LITERATURE CITED

Allen, J.D. and A.S. Flecker. 1993. Biodiversity conservation in running waters. *Bio-Science* **43**: 32-43.

Cabeçadas, L. 1998. Phytoplankton production in the Tagus estuary (Portugal). *Oceanologica Acta* **22**: 205-214.

Chon, S.H. and J.O. Bae. 1999. Speciation of phosphorus in Lake Imha sediments. Proceeding of Journal of Korean Society on Water Quality. 86-89.

Cloern, J.E. 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. *Continental Shelf Research* **7**: 1367-1381.

Cole, J.J., N.F. Caraco and B.L. Peierls. 1992. Can phytoplankton dynamics in the northern San Francisco Bay estuary, *Estruarine Coastal Shelf Sci*. **16**: 415-429.

De Ceballos, B.S.O., A. König and J.F. Oliveira. 1998. Dam reservoir eutrophication: a simplified technique for a fast diagnosis of environmental degradation. *Water Research* **32**: 3477-3483.

Flemer, D.A. 1970. Primary production in the Chesapeake bay. *Chesapeake Science* **11**: 117-129.

Grayson, R.B., B.L. Finlayson, C.J. Gippel and B.T. Hart. 1996. The Potential of field Turbidity Measurements for the Computation of Total Phosphorus and Suspended Solids Loads. *Journal of Environmental Management* **47**: 257-267.

Ha, K., H.W. Kim and G.J. Joo. 1998. The phytoplankton succession in the lower part of hypertrophic Hankdong River (Mulgum), South Korea. *Hydrobiologia* **369/370**: 217-227.

Ha, K., M.H. Jang and G.J. Joo. 2002. Spatial and temporal dynamics of phytoplankton communities along a regulated river system, the Nakdong River, Korea. *Hydrobiologia* **470**: 235-245.

Harris, G.P. 1986. Plankton Ecology-Structure, Function and Fluctuation. Chapman and Hall, New York.

Hart, R.C. 1990. Zooplankton distribution in relation to turbidity and related environmental gradients in a large subtrophical reservoir: patterns and implications. *Freshwat. Biol*. **24**: 241-263.

Heo, W.M., B.C. Kim, Y. Kim and K.S. Choi. 1998. Storm runoff of phosphorus from nonpoint sources into Lake Soyang and transportation of turbid watermass within the lake. *Korean J. Limnol*. **31**(1): 1-8.

Horppila, J. and L. Nurminen. 2003. Effects of submerged macrophytes on sediment resuspension and internal phosphorus loading in Lake Hidenvesi. *Water Research* **37**: 4468-4474.

Irigoien, X. and J. Castel. 1997. Light Limitation and Distribution of Chlorophyll Pigments in a Highly Turbid Estuary: the Gironde (SW France). *Estuarine, Coastal and Shelf Science* **44**: 507-517.

Joo, G.J., H.W. Kim, K. Ha and J.K. Kim. 1997. Long-term trend of the eutrophication of the lower Nakdong River. *Korean J. Limnol*. **30**: 472-480.

Kim, H.W., K. Ha and G.J. Joo. 1998. Eutrophication of the lower Nakdong River after the construction of an estuarine dam in 1987. *Internat. Rev. Hydrobiol*. **83**: 65-72.

Kim, H.W. and G.J. Joo. 2000. The longitudinal distribution and community dynamics of zooplankton in a regulated large river: a case study of the Nakdong River (Korea). *Hydrobiologia* **438**: 171-184.

Kim, H.W., G.J. Joo and N. Walz. 2001. Zooplankton dynamics in the hypereutophic Nakdong River system (Korea) regulated by an estuary dam and side channels. *Internat. Rev. hydrobiol*. **86**: 127-143.

Kim, H.W., G.H. Chang, K.S. Jeong and G.J. Joo. 2003. The spring metazooplankton dynamics in the river-reservoir hybrid system (Nakdong River, Korea): Its role in controlling the phytoplankton biomass. *Korean J. Limnol*. **36**(4): 420-426.

Koerner, S., 2001. Development of submerged macrophytes in shallow Lake Mueggelsee (Berlin, Germany) before and after its switch to the phytoplankton dominated state. *Arch. Hydrobiol*. **152**: 395-409.

Korea Water Resources Corporation (KOWACO). 1994. Causes of turbidity increase in the Imha Reservoir: final report.

Lee, K.S., D.K. Ko, J.H. Park and E.H. Hwang. 2004. Sediment flux in the area of Lake Imha using GIS. Report of KOWACO.

Lee, J.E. 2003. Effects of turbid water in the Imha Lake on aquatic ecosystem. Report.

Lee, S.G. and B.H. Kang. 2001. Effect of overhead flooding stress on photosynthesis and growth in rice. *Korean J. Crop Sci.* **46**: 209−214.

Moss, B. 1998. Ecology of Fresh Waters: Man and Medium, Past to Future. 3rd ed. Blackwell Science, Oxford.

Muylaert, K. and K. Sabbe. 1999. Spring phytoplank assemblages in and around the maximum turbidity zone of the estuaries of the Elbe (Germany), the Schelde (Belgium / The Netherlands) and the Gironde (France). *Journal of Marine Systems* **22**: 133−149.

Park. S.B. 1998. Basic water quality of the mid to lower part of Nakdong River and the influences of the early rainfall during monsoon on the water quality. M. S. thesis. Pusan National University, Busan, 89p.

Reynolds, C.S. 1984. The Ecology of Freshwater Phytoplankton. Cambridge University Press, NY, 384p.

Round, F.E., R.M. Crawford and D.G. Mann. 1990. The Diatoms, Cambridge University Press, New York.

Shiel, R.L. and K.F. Walker. 1984. Zooplankton of regulated and unregulated rivers: the Murray−Darling system, Australia. In A. Lillehammer and S.J. Saltviet (eds), Regulated Rivers. University of Oslo Press: 263−270.

Shin, J.K., C.K. Kang and S.J. Hwang. 2003. Daily variations of water turbidity and particle distribution of high turbid−water in Paltang Reservoir, Korea. *Korean J. Limnol.* **36**(3): 257−268.

Shin, J.K., S.A. Jeong, I. Choi and S.J. Hwang. 2004. Dynamics of turbid water in a Korean reservoir with selective withdrawal discharges. *Korean J. Limnol.* **37**(4): 423−430.

Shin, J.K. and S.J. Hwang. 2004. Development and dynamics of turbid water in the lotic and lentic ecosystems, Korea. Annual Meeting Congress, Korea Society Limnology in 2004.

Thornton, K.W., B.L. Kimmel and F.E. Payne. 1990. Reservoir Limnology: Ecological Perspectives. Wiley and Sons, New York.

Walker, T.R., S.D. Young, P.D. Crittenden and H. Zhang. 2003. Anthropogenic metal enrichment of snow and soil in north−eastern European Russia. *Environmental Pollution* **121**: 11−21.

Wetzel, R.G. and G.E. Likens. 1991. Limnological Analyses. 2nd ed. Springer−Verlag, New York.

Zar, J.H., 1984. Biostatistical Analysis. 2nd ed. Prentice−Hall, New Jersey.

(Manuscript received 3 December 2004,
Revision accepted 20 February 2005)