Korean J. Limnol. 36 (4): 420~426 (2003)

The Spring Metazooplankton Dynamics in the River-Reservoir Hybrid System (Nakdong River, Korea): Its Role in Controlling the Phytoplankton Biomass

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During a three-year study (2000-2002), dramatic changes in the phytoplankton biomass and high transparency were repeatedly observed during mid-spring in the lower part of the Nakdong River. Rotifers (*Brachionus, Keratella, Polyarthra*), sharply increased toward the middle and end of spring. As hydrologic retention time increased (to near 20 days) and water temperature increased from 10°C to >20°C toward the end of spring, small cladocerans noticeably increased. Once phytoplankton biomass passed their peak stage in the mid-spring, a short period (one or two weeks) of relatively low phytoplankton biomass and high Secchi transparencies occurred. Grazing by the zooplankton was highest in spring, thus, it seems that high grazing activities of zooplankton grazing regulated phytoplankton dynamics in the river. The results indicate that the role of zooplankton grazing in controlling the phytoplankton biomass becomes more important during the spring when river water is relatively stagnant.

Key words : zooplankton grazing, phytoplankton biomass, hydrologic retention, regulated river, Nakdong River

INTRODUCTION

Zooplankton grazing has long been recognized as an important factor that regulates the biomass and species composition of phytoplankton in lakes (Porter, 1977). At high densities of macrozooplankton, the transparency of even highly eutrophic lakes can increase substantially (Brock, 1985; Gawler *et al.*, 1988). This phenomenon has been described as a "clear-water phase" and in the PEG-model, it is attributed to direct limitation of phytoplankton by zooplankton grazing (Sommer *et al.*, 1986).

Relative to lakes there has been considerably less research related to zooplankton dynamics in rivers. Early studies focused on taxonomic composition (Hutchinson, 1939; Greenberg, 1964), while during the 1970's and 1980's emphasis was directed towards the studies of seasonal and spatial dynamics and the accumulation of biomass (Rai, 1974; Shiel *et al.*, 1982; Saunders and Lewis, 1989). More recent research has considered other aspects of river zooplankton dynamics, including interactions between phytoplankton and zooplankton, and the factors regulating plankton abundance (Thorp *et al.*, 1994; Kobayashi *et al.*, 1996; Basu and Pick, 1997; Viroux, 1997).

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Many large rivers in industrial nations have become hydrologically regulated, and free-flowing reaches of the rivers have become chains of reservoirs. In a study of plankton dynamics in the Murray-Darling River System, Shiel and Walker (1984) drew a clear distinction between regulated and unregulated rivers when describing their plankton. The impact of zooplankton and macrobenthos grazing on phytoplankton in river systems is noted by several authors (Jones and Barrington, 1985; de Ruyter van Steveninck *et al*., 1990) and simulation studies indicate a potentially important role for zooplankton grazing in river plankton food webs (Descy *et al*., 1987).

Most Korean rivers became highly regulated and eutrophicated during the last two decades. Morphological and hydrological changes in the rivers caused dramatic shifts in the community structure of plankton (Kim *et al*., 1998; Kim and Joo, 2000). The objective of the present study is to describe the interaction between zooplankton and water quality in a regulated river system, with a focus on the spring season. This study contributes to an improved understanding of plankton dynamics in regulated rivers and adds to the relatively limited body of data available on the grazing activity of river zooplankton.

MATERIALS AND METHODS

Study site

The Nakdong River (Fig. 1) is one of the four major river systems in South Korea (length: 528 km, total drainage area: 23,818 km^2). Its watershed is located between 35-37°N and 127-129° E. The river shows typical characteristics of large Korean rivers, being hydrologically regulated by a series of multipurpose dams in the headwater tributaries and middle part of the river, and by barrages in the estuary. The construction of the dam also accelerated the eutrophication of the river (Kim *et al*., 1998). The consistently high nutrient levels, along with high phytoplankton biomass, would classify the lower Nakdong River as hypereutrophic (Kim *et al*., 1999; Kim *et al*., 2000; Kim *et al*., 2002). The lower river also experienced blooms of blue-green algae (*Microcystis* spp.) and diatoms (*Stephanodiscus hantzschii*) (Ha *et al*., 1998; Ha *et al*., 1999).

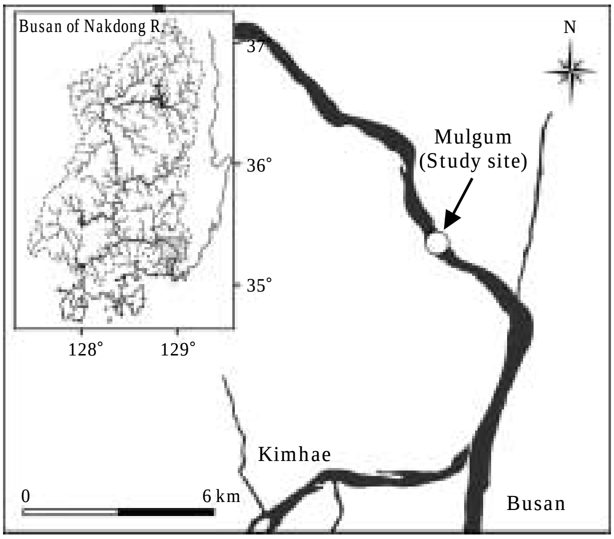

Fig. 1. Map showing the basin of the Nakdong River and study site (Mulgum: RK 27).

Sampling procedures and measured physical factors and chl. *a* concentration

Sampling was carried out in the lower Nakdong River (Mulgum, RK; river kilometer; above 27 km from the estuary dam) on a weekly intervals from 2000 to 2002. Water samples were obtained from 0.5 m depth with a Van Dorn sampler, placed into 20 L sterile polyethylene bottles, and kept in the shade at ambient temperatures until return to the laboratory (within 1 h of collection). Secchi transparencies were determined with a 20 cm disk, while water temperature and dissolved oxygen were measured with a YSI Model 58 meter. Water samples (100-300 mL) for the determination of chl. *a* were filtered through 0.45 μm cellulose acetate membranes and stored frozen until analysis. Chl. *a* concentrations were determined with a spectrophotomer using the monochromatic method described in Wetzel and Likens (1991). River discharge rates at the estuary dam were obtained from the Flood Control Center in Pusan, Korea.

Zooplankton sample collection and enumeration

For the determination of zooplankton density and biomass, 8 L samples of water were collected from 0.5 m depth. The collected water was filtered through a 35 μm mesh net, and preserved with 10% (final concentration) formalin. Macrozooplankton (cladocerans and copepods) were counted at 50× magnification, and microzooplankton (nauplii and rotifers) were counted at 100× magnification using an inverted microscope. Zooplankton were identified to genus or species level (with the exception of juvenile copepods) according to Koste (1978), Smirnov and Timms (1983), Koste and Shiel (1987), and Bayly (1992).

Determination of zooplankton community filtration rates (CFR)

Community filtering rate (CFR; ml L^{-1} h^{-1}) was determined as the sum of specific filtering rates form all taxa observed. Zooplankton community filtration rates were directly measured based on population densities of each species, and individual filtering rates (ml $individual^{-1}$ h^{-1}) were conducted on 17 occasions from March to June in 1998 (Kim, 1999; Kim *et al.*, 1999), 2001 and 2002.

RESULTS

Hydrologic and physical features

Hydrologic data indicate that the annual discharge cycle of the Nakdong River was typical of the monsoon region of northeastern Asia. Discharge in the lower river was highly variable (Fig. 2A). Peak discharge occurred in the summer (June–August) as a result of flooding during the monsoon in early summer and after typhoons in late summer. During the spring (March–May), discharge at the estuary dam was lower. Sharp increases in water temperature, typically from 5°C to 20°C, were observed from March to May (Fig. 2A). The river was very turbid and Secchi transparencies of <80 cm were observed during both phytoplankton blooms and flooding events. In the middle and late spring, short period (one or two weeks) of high transparency (Secchi depth >100 cm) was repeatedly observed (Fig. 2B).

Zooplankton community and species development in spring

The zooplankton community was strongly dominated by planktonic rotifers. During the spring, rotifers comprised more than 90% of the total zooplankton abundance, while cladocerans acco-

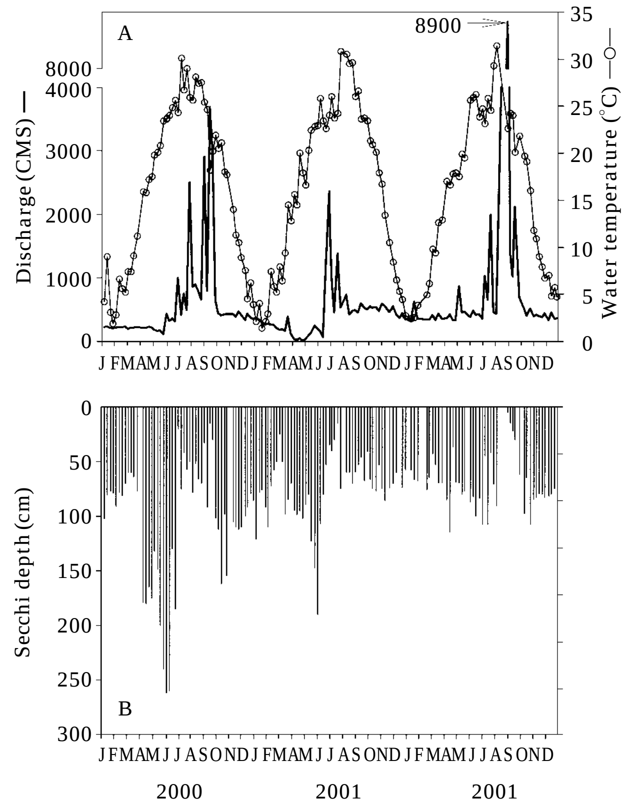

Fig. 2. Changes of discharge (Samrangjin: ca. RK 47) and physical parameters in the lower Nakdong River (Mulgum) during 2000–2002 (A: Discharge and Water temperature, B: Secchi depth).

unted for 5%, followed by copepods (1–4%). The relative abundance of cladocerans and copepods generally increased in late April through May, until these groups accounted for >30% of total zooplankton abundance (Fig. 3).

Brachionus spp., *Keratella* spp., and *Polyarthra* spp. were the most dominant rotifer taxa in the lower river. *Brachionus* was represented by seven species, and it was the most abundant genus in spring, reaching a peak density of >1,000 ind./L in early spring. Subsequently this taxon's abundance rapidly declined, and it became rare in June (Fig. 4). Both *Polyarthra* and *Keratella* accounted for 20–30% of the total rotifer abundance. Their abundances were highest from late April to June (Fig. 4).

The peak abundance of cladocerans in spring generally occurred one or two months later than that of the rotifers, although there was inter-annual variation in it's density peak timing. *Bosmina longirostris* was the dominant cladoceran

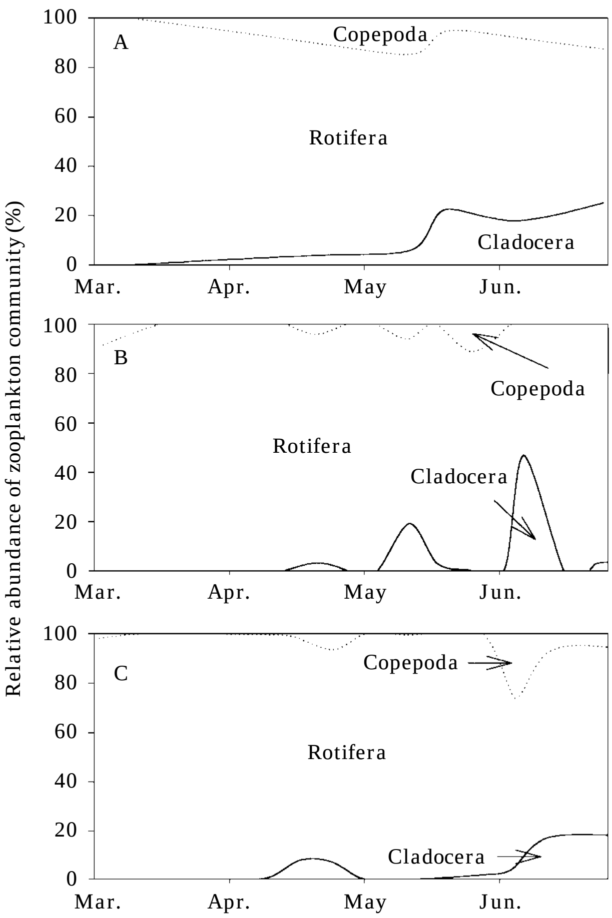

Fig. 3. Relative abundance of zooplankton community (%) during the spring based on the total abundance (Ind./L) (A: 2000, B: 2001, C: 2002).

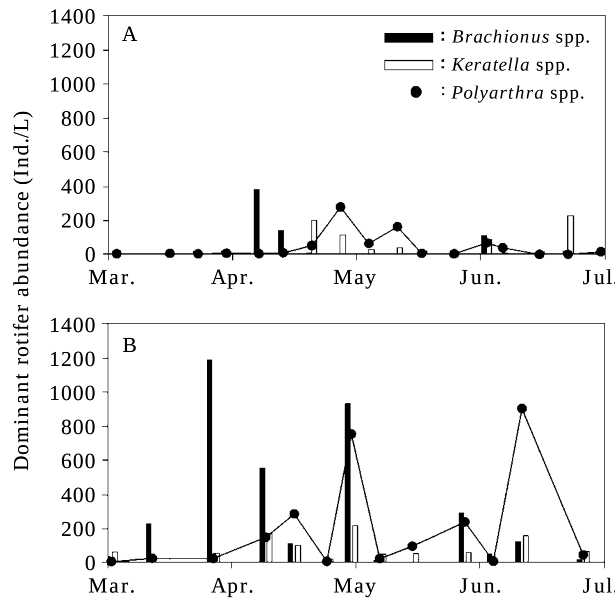

Fig. 4. Changes of dominant rotifer species during the spring (A: 2001, B: 2002).

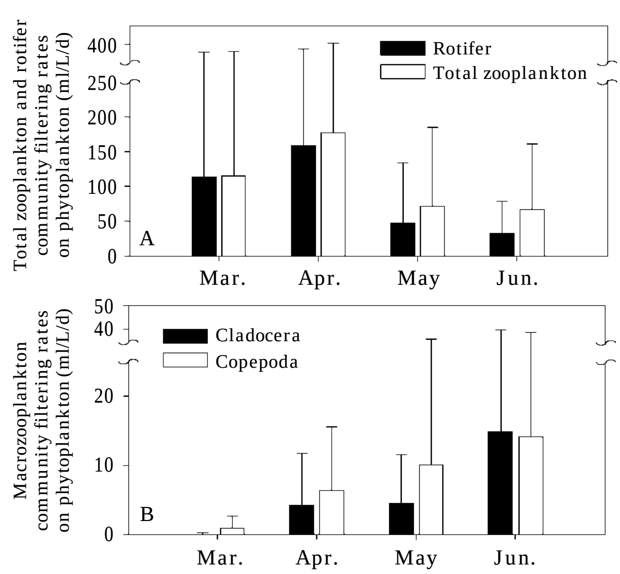

Fig. 5. Monthly changes of total zooplankton, rotifer, cladocera, and copepoda community filtration rates on phytoplankton (CFR: ml L^{-1} d^{-1}) during the spring (2000–2002, mean±s.d., n = 9–10, respectively) (A: rotifer and total zooplankton, B: cladoceran and copepoda).

species and reached its peak abundance in April and May 2000, 2001 and 2002. It accounted for most of the steep rise in total cladoceran abundance during the spring. In the late spring of 2002, the highest cladoceran density was due to the larger species *Diaphanosoma brachyurum*.

Zooplankton grazing activity in spring

The pattern of total zooplankton grazing in spring varied from year to year. However, maximal total zooplankton community filtering rates (CFR: ml L^{-1} d^{-1}) and rotifer CFR generally occurred in April (Fig. 5A). Grazing by cladocerans and copepods tended to reach its peak just after the peak in rotifer CFR (Fig. 5B).

Brachionus spp. and *Polyarthra* spp. contributed more to the total rotifer CFR than did the other species. The grazing activity of *Brachionus* spp. was highest in early spring (March–April) while that of *Polyarthra* spp. was highest during the late spring. Two cladoceran taxa (*B. longirostris* and *D. brachryurum*) accounted for more

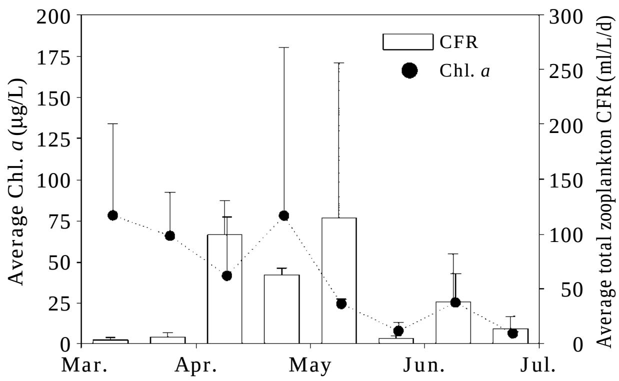

Fig. 6. Monthly changes of average total zooplankton CFR (ml L^{-1} d^{-1}) and phytoplankton biomass (chl. *a*) during the spring (2000–2002, mean±s.d., n = 4–5, respectively).

than 50% of total cladoceran CFR. Distinct changes in phytoplankton biomass (chl. *a*) corresponded with the zooplankton CFR in spring (Fig. 6). Considering the spring season, there was an inverse relationship between chl. *a* and CFR. Phytoplankton biomass consistently declined during the spring period.

DISCUSSION

A reduction of algal biomass (chl. *a*) was repeatedly observed to coincide with a spring peak of zooplankton abundance in the lower Nakdong River, Korea. The inverse relationship between zooplankton and phytoplankton with clear water has been frequently reported in natural lakes (Anderson *et al.*, 1955; Crumpton and Wetzel, 1982; Lampert, 1985; Sommer *et al.*, 1986). Zooplankton-induced clear water phases also have been reported in some large rivers, but the finding is not as common as in lakes. Basu and Pick (1997) found no strong relationship between phytoplankton and zooplankton in a lowland temperate river while reductions of phytoplankton due to grazing were reported in the River Meuse (Descy *et al.*, 1987; Gosselain *et al.*, 1994), and the River Rhine (de Ruyter van Steveninck *et al.*, 1990). Though the lower Nakdong River has become a "reservoir-river hybrid" type and hypereutrophic due to anthropogenic nutrient inputs, short-term (one or two weeks) of low chl. *a* and high transparency (Secchi depth >100 cm) have been repeatedly observed during mid-spring.

In both lakes and rivers, it has been suggested that the clear-water phase is caused (in part) by factors other than zooplankton grazing, including nutrient limitation and light inhibition. For example, de Ruyter van Steveninck *et al.* (1992) indicated that the diatom-dominated phytoplankton depleted the dissolved silicate in the River Rhine and this led to a collapse of their populations in spring. In the Nakdong River, a spring deficiency in nutrients (PO_4-P, NH_4-N, NO_3-N and SiO_2) is unlikely to be responsible for the clear-water phase (Kim, 1999). Rapid declines in phytoplankton biomass in the river were not significantly related to changes in the concentration of these soluble nutrients ($p > 0.1$, for all biomass *vs.* nutrient regressions). In fact, nutrient concentrations were highest at the time when phytoplankton densities were maximal.

The evidence of light inhibition of the spring phytoplankton community is also weak in the river. Alpine and Cloern (1988) suggested that light limitation should be considered when $z_p : z_m$ is < 0.2 (z_p: thickness of the euphotic layer, z_m: thickness of the surface mixed layer). In the Nakdong River, $z_p : z_m$ usually was > 0.5 due to the shallow depth (approximately 4 m). Likewise, a reduction of the phytoplankton due to river discharge was unlikely. Even though an inverse relationship between phytoplankton biomass and discharge rate has been demonstrated in other rivers (Jones and Barrington, 1985; Reynolds, 1988), the water body of the Nakdong River was a hydrologically stable during spring with low rates of discharge (< 50 m^3/sec) and flushing ($<$ 5% per day) were maintained. Thus, we conclude that grazing by zooplankton was the main factor responsible for the decreases in phytoplankton biomass.

In comparison to the level of zooplankton biomass in lakes and reservoirs at the beginning of a clear-water phase, the total biomass of zooplankton in the river was relatively high ($>$ 4,000 μg/L dry weight) (Kim, 1999). This may reflect the composition of the grazer assemblage. In lakes, the major group responsible for active grazing is macrozooplankton, in particular large-bodied members of the genus *Daphnia*. These large animals have high individual grazing rates and can exert considerable grazing pressure on the phytoplankton at relatively low densities. Rotifers, on the other hand, have low individual rates of grazing. Our finding that a clear water phase can occur where the dominant zooplankton are rotifers and small cladocerans is particular interest, because to our knowledge, it has not been previously reported. As free−flowing segments of rivers throughout the world become hydrologically modified due to increasing demands of water resources, increased retention time will likely become an important factor affecting the ecology of those systems. Sections of the rivers will periodically come to resemble lakes, and may display lacustrine plankton dynamics, such as the clear water phases observed here. Such changes have the potential to affect the functioning of the entire river food web, and should be the focus of additional research.

ACKNOWLEDGEMENT

This work was supported by grant No. R05200-20000119302002 from Korean Science & Engineering Foundation.

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(Manuscript received 1 November 2003,
Revision accepted 15 December 2003)

<국문적요>

강-저수지 복합형 시스템내 봄 동물플랑크톤의 역동성 (낙동강, 한국): 식물플랑크톤 생체량 조절자로서의 역할

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지난 3년간(2000-2002), 식물플랑크톤 생체량의 역동적인 변화와 높은 투명도가 봄의 중순 기간 동안 낙동강 하류 부분에서 반복적으로 관찰되었다. 윤충류들은(*Brachionus, Keratella, Polyarthra*), 봄의 중순과 늦봄 기간 동안에 급격히 증가하였다. 늦봄 기간 동안 수체의 잔류시간의 증가(약 20일 정도)와 수온의 상승시기에, 10°C로 부터 20°C 이상, 지각류의 증가를 나타내었다. 봄의 중순 높은 식물플랑크톤 생체량 시기 이후, 짧은 기간(약 1-2주) 동안 낮은 식물플랑크톤 생체량과 높은 세키 투명도가 본 조사지점에서 나타났다. 봄 기간 동안 동물플랑크톤의 섭식률은 매우 높으며, 이러한 동물플랑크톤의 높은 섭식 활성도는 식물플랑크톤 동태를 조절하는 것으로 사료된다. 본 연구 결과는 강의 수체가 다소 정체되어 있는 봄 기간 동안 식물플랑크톤 생체량의 조절은 동물플랑크톤의 섭식에 의해 조절될 수 있음을 시사한다.