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Time Lags between Hydrological Variables and Phytoplankton Biomass Responses in a Regulated River (the Nakdong River)

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ABSTRACT: This study describes time lag responses between hydrological variables and phytoplankton biomass in a regulated river system, the lower Nakdong River in South Korea. The lower Nakdong is a typical flow-controlled lotic system, and its limnological characteristics are influenced by climatic variation such as monsoons and summer typhoons. Mean rainfall in the area during summer is about 1,200 mm, which comprises >60% of annual rainfall. Our results show that the regulation of flow in the Nakdong by multi-purpose dams from 1995 to 2004 affected phytoplankton dynamics. Diatom blooms occurred in winter, when the limited discharge allowed for proliferation of the phytoplankton community. Using multiple regression analysis, we detected significant time-delayed relationships between hydrological variables and phytoplankton biomass. These results may be useful for water resource managers, and suggest that 'smart flow' control would improve water quality in large regulated river systems of the Republic of Korea.

Key words: flow control, lower Nakdong River, phytoplankton biomass, regulated river

INTRODUCTION

A variety of factors affect the dynamics of river ecosystem, but the total amount of seasonal precipitation is probably the most influential factor affecting river ecosystem dynamics (Bauder 2005). The flow pattern in the river channel is the primary driving factor for most rivers, because river ecosystems are usually characterized by flow regulation (Stober and Nakatani 1992), which affects both the morphological characteristics and the hydrological patterns of streams (Lamouroux and Souchon 2002). Numerous dams and locks have been constructed along rivers during the last few decades, mainly due to high demand for water resources for human use (Tharme 2003) and, many researchers have examined the influence of flow regulation on the ecology of lotic systems (Maheshwari et al. 1995, Rader and Belish 1999, Bertrand et al. 2001, Maier et al. 2001, Reyjol et al. 2001, Azami et al. 2004, Joo and Jeong 2005).

Flow regulation, and the resulting increased water retention time, may lead to deterioration in water quality due to increased concentrations of nutrients or increased probabilities of proliferation of specific types of phytoplankton. Regulated flow in lotic systems may also negatively impact water quality and habitat quality during dry seasons (Schleiter et al. 1999, Lekka et al. 2004). In regions showing clear climate seasonality, flow regulation may have a significant impact on water quality in rivers. For example, flow regulation by dams in upper tributaries of the lower Nakdong River had a delayed and periodic influence on the growth of two bloom-forming phytoplankton species (Jeong et al. 2007). However, water quality in dammed rivers can be maximized by the implementation of a well-managed 'smart-flow' strategy for dam hydrology, particularly in regions with high periodicity of meteorological-hydrological factors (i.e. distinct rainy and dry seasons).

The Nakdong River supplies water resources to approximately 10 million residents in and around the catchment. In order to efficiently provide water resources given the dramatic differences in rainfall between summer

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*Corresponding Author; Phone: +82-51-510-2258, e-mail: pow5150@pusan.ac.kr and winter, multi-purpose dams were built in the upper part of the river, and an estuarine barrage was constructed in the estuary. Flow regulation by these artificial structures, however, has resulted in stagnant water flow, which has caused drastic changes in the river's hydrologic features and accelerated eutrophication in the river (Ha et al. 1998, Park et al. 2002).

Water resource management in the Nakdong is focused on the summer rainfall, and control of the river flow is believed to have resulted in changes in plankton community dynamics in the lower Nakdong (Kim 1999, Ha et al. 2000, Kim and Joo 2000, Kim et al. 2001, Ha et al. 2002, Kim et al. 2003). Jeong et al. (2007) described time-series relationships between two bloom-forming phytoplankton species and hydrological changes in the Nakdong River, but detailed quantitative analyses of the influence of changes in river flow on 'total phytoplankton' dynamics have not yet been conducted. Further research on the relationship between hydrological changes and their ecological consequences will be important as it will advance both our understanding limnological dynamics and permit more effective water quality management.

In this study, we used long-term limnological data to explore the relationship between hydrological conditions in the lower Nakdong River, a typical example of a 'regulated river' (Jeong et al. 2003, Joo and Jeong 2005, Jeong 2007), and phytoplankton biomass. We used various time fractions of hydrological dynamics data to develop a predictive model for changes of phytoplankton biomass (estimated using chlorophyll *a* concentrations, chl-*a*), and the most significant time-series relationships were investigated. The results of this study provide information about the relationship between hydrology and water quality that can be used for further in-depth modeling of water quality processes.

MATERIALS AND METHODS

Description of the study site

The Nakdong River lies in the southeastern part of the Korean peninsula (N 35-37°, E 127-129°; Fig. 1), and is approximately 526 km in length with a catchment area of about 23,817 km^2. Our study site, Mulgum (transliterated as Mulgeum in some documents), is located 27 km from the estuarine barrage. This site experiences two annual phytoplankton proliferations: summer cyanobacterial blooms and winter diatom blooms (Ha et al. 1998, Jeong et al. 2001). Approximately 80% of the population (~ 4,000,000) of the Busan Metropolitan area depends on water resources from the lower part of the Nakdong River.

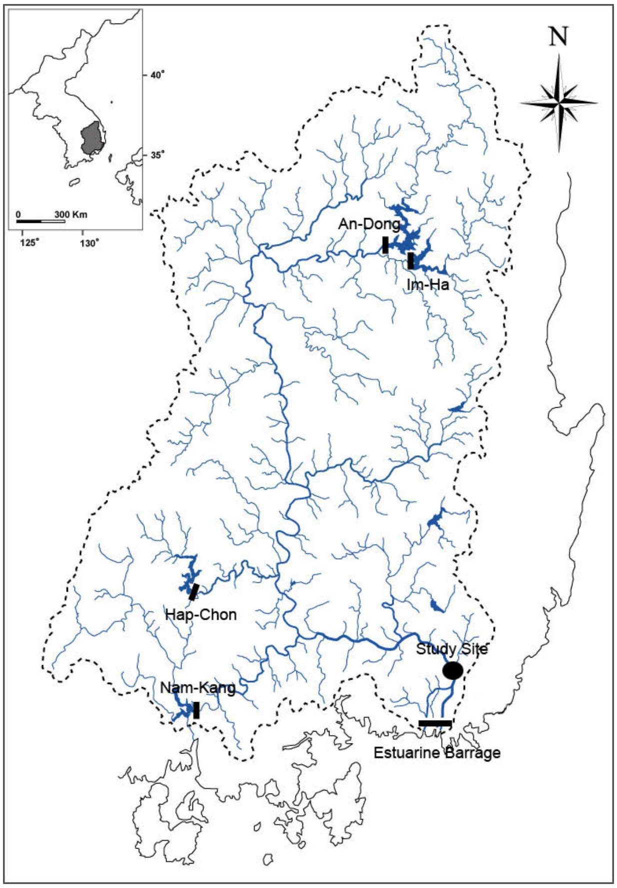

Fig. 1. Map of the Nakdong River basin and the study site. (▮: dam, ●: Mulgum study site, distance of the river from the estuarine barrage: 27 km)

Data collection

Water samples were collected at a 0.5 m depth biweekly from 1995 through 2004 to measure the phytoplankton biomass. The chl-*a* concentration was determined spectrophotometrically following acetone extraction (Wetzel and Likens 1991). For our analysis of the river's hydrological characteristics, we quantified rainfall in the river basin, discharge from the multi-purpose dams, river discharge, water velocity, and river depth at the study site. We divided the entire river basin into 34 sub-basins, and calculated averages from the rainfall data from 32 sub-basins located above the study site using Kriging to obtain the average rainfall for the basin during the study period. We obtained daily dam discharge data measured at four major multi-purpose dams (i.e. the Andong (A-), Imha (I-), Hapchon (H-) and Nam River (N-) dams) from the Nakdong River Flood Control Center.

We measured daily river flow using a Soil and Water Assessment Tool (SWAT) based on river basin data. We constructed a model for the entire river basin, considering rainfall, discharge, dam hydrology, and water abstraction

Table 1. Variables selected by the forward selection method. The 'n-day' expression indicates the number of days averaged for each of parameter

Raw data		Conc. of Chl-*a*		Chl-*a* loading (/10)	
		Raw	Normalized	Raw	Normalized
Discharge at M-study site	Average / 1, 3, 5, 7day (M-1dQ, M-3dQ, M-5dQ, M-7dQ)	M-1dQ	m-1dQ	M-7dQ	m-1dQ
Water velocity at M-study site (X 1000)	Average / 1, 3, 5, 7day M-1dV, M-3dV, M-5dV, M-7dV	M-3dV	m-3dV	-	-
Water depth at M-study site (X 10)	Average / 1, 3, 5, 7day M-1dH, M-3dH, M-5dH, M-7dH	M-5dH	m-5dH	-	-
Discharge at A-dam	Average / 1, 5, 10, 15day A-1dQ, A-5dQ, A-10dQ, A-15dQ	A-15dQ	a-15dQ	A-15dQ	a-1dQ
Discharge at I-dam	Average / 1, 5, 10, 15day I-1dQ, I-5dQ, I-10dQ, I-15dQ	I-5dQ	i-5dQ	I-15dQ	i-5dQ
Discharge at H-dam	Average / 1, 5, 10, 15day H-1dQ, H-5dQ, H-10dQ, H-15dQ	H-1dQ	h-1dQ	H-10dQ	h-1dQ
Discharge at N-dam	Average / 1, 5, 10, 15day N-1dQ, N-5dQ, N-10dQ, N-15dQ	N-5dQ	n-5dQ	N-15dQ	n-5dQ
Rainfall in basin	Monthly average N-rain	N-rain	n-rain	N-rain	n-rain

using hydrological data from the major seven dams, the main channel and the primary tributaries of the Nakdong River, and produced a total of 176 Hydrological Response Units (HRUs) covering the 34 sub-basins (covering 10% of the land use and soil maps). The study period was from 1994 to 2004, and we evaluated the model using the last nine years of data, due to simulation stabilization. We validated the model using daily discharge data from one site (Jindong, approximately 55 km from the study site in the main channel of the Nakdong River) where the observed data had a relatively high reliability. Daily river discharge, water velocity and depth for the study site were produced using the validated model output for the modeled years (1994-2004).

Although the phytoplankton levels were monitored biweekly, the monitoring interval was slightly irregular (i.e., two weeks ± 1-2 days). Therefore, we used monthly summed (for rainfall only) or averaged data for further statistical analysis.

We used discharge and rainfall for each dam and study site for the analyses of the relationship between hydrological variables and phytoplankton biomass, and limnological values were calculated using forward selection. Variables with high correlation coefficients were selected for statistical analysis (Table 1). Furthermore, we attempted to use two types of chl-*a* value; one was chl-*a* concentration and the other was chl-*a* loading. The chl-*a* loading is the value obtained when discharge value is multiplied into the concentration, and it is more frequently utilized in the field of hydrological modeling (Kang and Hyun 1997, Han et al. 2007).

The data were organized into twenty-two formats reflecting various sets of conditions (Table 3) for the multiple regression (MR) analyses, which took temporal variability into consideration. Seasonal averages was calculated for four seasons (spring = March-May; summer = June-January; autumn = September-November; winter = December-February), and rainfall for each of the study ten years was classified into one of three categories (i.e., dry, normal or wet) based on mean ± standard seviation (S.D.) rainfall for each season. Dry and wet years were defined from the ranges of mean ± S.D.

Statistical analysis

The dataset was converted to monthly averages because the hydrological data had been measured daily and the phytoplankton biomass (chl-*a*) was determined biweekly. Monthly data were transformed into normalized data using the minimum-maximum method, so that the transformed values ranged from 0 to 1. Two statistical analysis methods, correlation analysis and multiple regression (MR) analysis, were used to reveal relationships between phytoplankton biomass and hydrological factors, with a maximum lag of 24 months for the MR analyses. The correlation analysis shows the direct relationship between hydrological dynamics and phytoplankton abundance, and the MR analysis enables us to understand the potential time-series influence of river regulation on

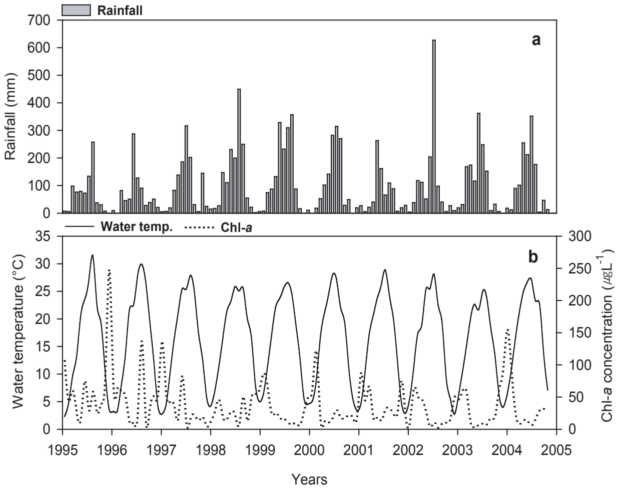

Fig. 2. Annual changes in rainfall (a), water temperature, and chl-*a* concentration (b) at the study site.

the determination of phytoplankton dynamics.

RESULTS

The Nakdong River lies in the monsoon region of northeastern Asia, where >60% of rainfall occurs in the summer (June to September). Mean precipitation during this period is approximately 1,200 mm (standard error, S.E.: 26.8; Fig. 2a). The mean water temperature in the river was 16.4°C (S.E.: 0.77), with the maximum water temperature usually occurring in August (25-30°C). No significant relationship between chl-*a* and water temperature was detected, but the chl-*a* level was higher at lower water temperatures (October to April; Fig. 2b).

The discharges for each multi-purpose dam are shown in Fig. 3. The average hourly discharges of the I-dam (26 ton/h), the A-dam (36 ton/h) and the H-dam (23 ton/h) were lower than that of the N-dam (83 ton/h). The average discharge for the study site (481 ton/h) was significantly higher than that for the multi-purpose dams in the upper part of the river, and reached a maximum value of 2,350 tons/h in September 2002. Time-series changes in discharge for the study area (M-1dQ) were similar to those for the N-dam discharge (N-5dQ). Monthly averages of water velocity and water depth in the study site varied little, and changed smoothly over time, without noticeable effects from seasonal variables.

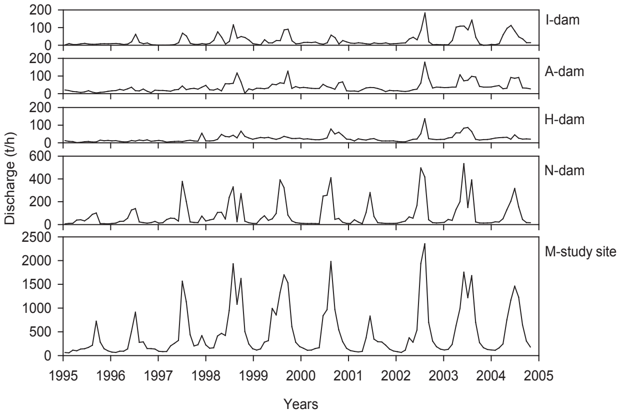

Fig. 3. Annual variation in discharge.

The results of the correlation analysis for hydrological factors and phytoplankton biomass are shown in Table 2. The study site water depth for (M-5dH) was significantly correlated with water velocity (M-3dV) (r = 0.99, n = 120). The discharge for the study site (M-1dQ) was correlated with the discharge from the N-dam (N-5dQ) (r = 0.89, n = 120). Relatively high correlations were also observed between the discharge at the study site (M-1dQ) and the I-dam and A-dam discharges (I-5dQ, A-15dQ). Rainfall was correlated with discharge for the study site and the N-dam.

A significant time-delayed relationship between hydrological variables and phytoplankton biomass was derived from the MR analysis (Fig. 4). As the time lag increased, the relationship switched from positive to negative. Cases 1, 6, and 8 exhibited high negative correlations at a 0-2 months lag, and the most influential factor was study site water velocity (Fig. 4a, c, d). However, case 1L showed a positive correlation at 0-2 months lag, and the correlation coefficient for the water velocity was

Table 2. Correlation matrix among hydrology factors and chl-*a* (n = 120, α < 0.05, * indicates p < 0.05; ** indicates p < 0.01)

	Chl-*a*	M-1dQ	M-3dV	M-5dH	A-15dQ	I-5dQ	H-1dQ	N-5dQ	N-rain
Chl-*a*	1.00								
M-1dQ	-0.44^{**}	1.00							
M-3dV	0.20^{*}	-0.14	1.00						
M-5dH	0.20^{*}	-0.16	0.99^{**}	1.00					
A-15dQ	-0.33^{**}	0.70^{**}	-0.10	-0.14	1.00				
I-5dQ	-0.37^{**}	0.80^{**}	0.00	-0.02	0.66^{**}	1.00			
H-1dQ	-0.28^{**}	0.69^{**}	-0.19^{*}	-0.23^{*}	0.66^{**}	0.71^{**}	1.00		
N-5dQ	-0.39^{**}	0.89^{**}	-0.08	-0.10	0.52^{**}	0.71^{**}	0.60^{**}	1.00	
N-rain	-0.36^{**}	0.70^{**}	-0.10	-0.10	0.35^{**}	0.50^{**}	0.32^{**}	0.76^{**}	1.00

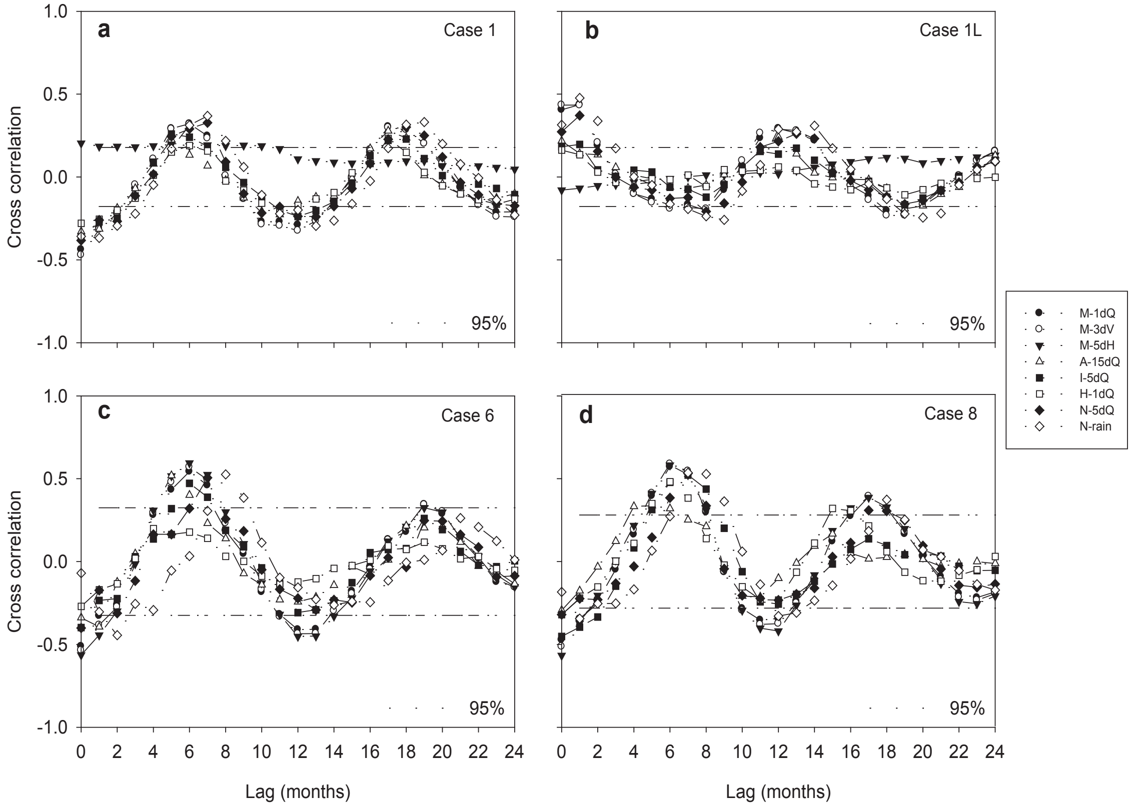

Fig. 4. Cross correlation of each factor: a (case 1)-monthly average of chl-*a*, b (case 1 L)-monthly average of chl-*a* loading, c (case 6)-monthly average of chl-*a* in wet years, d (case 8)-monthly average of chl-*a* in normal years.

the highest for this lag (Fig. 4b). The water depths for cases 1 and 1 L exhibited low correlation factors at larger time lags (Fig. 4a, b). However, there was a significant correlation with chl-*a* in cases 6 and 8 (Fig. 4c, d). Cases 1, 6, and 8 showed a lag of about 6 months in producing peak correlation coefficients. However, a 2-3 month lag was shown for a peak negative correlation in case 1 L. These results reveal that the phytoplankton community is influenced by hydrological effects.

Interestingly, for wet years (in case 6), the monthly average correlation of chl-*a* with rainfall in the Nam River (N-rain) had a different pattern than other variables. The correlation between N-rain and the chl-*a* concentration showed a one-month time lag in normal years and a two-month time lag in wet years. There was nearly no correlation between them at time zero (Fig. 4c), a result that was not consistent with the results of the correlation matrix (Table 2).

DISCUSSION

In the lower Nakdong River, the strength and timing of hydrological factors appear to influence phytoplankton population dynamics. Diatom proliferation is rare in most rivers, especially during winter (Ha and Joo 2000), but little is known about the reasons for this pattern. In other systems, most diatom blooms occur in spring or autumn (Muylaert and Sabbe 1998, Kolmakov et al. 2002, Scheffler and Morabito 2003). In this study, however, diatom blooms occurred in the lower Nakdong River in winter, and the proliferation of the phytoplankton community in winter occurred during only under a relatively limited range of discharge conditions. A higher density of phytoplankton was found with low discharge, while phytoplankton were apparently flushed away with larger discharges due to heavy rainfall. Low discharge in a stream may allow the greatest accumulation of benthic algae, which consist mostly of diatom species on the channel bed (Doyle et al. 2005). The primary variable affecting the hydrology of the Nakdong River is discharge or dam storage, and the results of the present study suggest that the characteristics and attributes of four major dams (i.e. Andong, Imha, Hapchon and Nam River dams) affect phytoplankton biomass (i.e. chl-*a* concentration) in the Nakdong River.

Generally, use of a correlation coefficients is one of the simplest ways to understand and explain the relationships among independent and dependent variables (Zar 1999). However, in this study, there were few meaningful

Table 3. MR analysis cases

Case of data utilization	with conc. of chl-*a*	with loading of chl-*a*
Monthly average	Case 1	Case 1L
Winter average (Dec.-Feb.)	Case 2	Case 2L
Spring average (Mar.-May)	Case 3	Case 3L
Summer (Jun.-Aug.)	Case 4	Case 4L
Autumn (Sep.-Nov.)	Case 5	Case 5L
Monthly average for wet years	Case 6	Case 6L
Seasonal average for wet years	Case 7	Case 7L
Monthly average for normal years	Case 8	Case 8L
Seasonal average for normal years	Case 9	Case 9L
Monthly average for dry years	Case 10	Case 10L
Seasonal average for dry years	Case 11	Case 11L

relationships between hydrological variables and chl-*a* concentrations occurring at the same time (Table 2), as ecological responses do not occur immediately in response to ultimate and proximate causes. Multiple time-series analysis based on cross correlation is an appropriate method for investigating time lag responses for ecological phenomena (Fig. 4).

Chl-*a* loading seemed to be more positively related to most hydrological variables than chl-*a* concentration (Fig. 4b), and rainfall in the Nam River dam (N-rain) elicited a different time lag response for the chl-*a* concentration than rainfall around the other dams. In normal years, the peak response to N-rain occurred approximately one more month later than that to rainfall around the other dams, and in wet years, the peak correlation for N-rain was delayed a further two months. In other words, the hydrologic impact of the Nam River dam could be distinguished from that of the other dams.

The Andong Dam is the largest dam in the Nakdong River basin, which means that it has the potential to be the most influential regulator of water flow. To date, only a few studies have described the effects of multipurpose dams (Jeong et al. 2007, Kim et al. 2007). Of the four major multipurpose dams in the catchment, only the Nam River Dam has two different discharge pathways (to the Nakdong River and to the ocean). Consequently, the direction of discharge from the Nam River can be switched depending on the conditions in the river. The results of this study suggest that strategies for regulating the discharge from the Nam River Dam should consider the approximately two-month time-delayed response in the Nakdong River basin.

The concept of effective discharge, or ‘Smart Flow’, may represent an important advance in the management of river ecosystems (Jeong et al. 2007). Furthermore, regulation of multipurpose dam discharge in winter appears to be particularly critical in northeast Asia, which is greatly influenced by monsoons. In summer, blooms of cyanobacteria can be controlled by frequent and torrential rainfall; however, careful management of water flow is required in winter to control the proliferation of diatoms in regulated river systems.

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LITERATURE CITED

Azami K, Suzuki H, and Toki S. 2004. Changes in Riparian vegetation communities below a large dam in a monsoonal region: Futase Dam, Japan. River Res Appl 20: 549-563.

Bertrand C, Siauve V, Fayolle S, and Cazaubon A. 2001. Effects of hydrological regime on the drift algae in a regulated mediterranean river (River Verdon, southeastern France). Regul River Res Manage 17: 407-416.

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

Ha K, Joo GJ. 2000. Role of silica in phytoplankton succession: an enclosure experiment in the downstream Nakdong River (Mulgum). Korean J Ecol 23: 299-307.

Ha K, Kim HW, Jeong KS, Joo GJ. 2000. Vertical distribution of Microcystis population in the regulated Nakdong River, Korea. Limnology 1: 225-230.

Ha K, Kim HW, Joo GJ. 1998. The phytoplankton succession in the lower part of hypertrophic Nakdong River (Mulgum), South Korea. Hydrobiologia 369/370: 217-227.

Han S, Shin HS, Kim S. 2007. Applicability of Load Duration Curve to Nakdong River Watershed Management. J Korean Soc Water Qual 23: 620-627.

Jeong JH, Yoon CG (Jr.), Donigian AS, Jung KW. 2007.

Development of the HSPF-Paddy model to estimate watershed pollutant loads in paddy farming regions. Agr Water Manage 90: 75-86.

Jeong KS, Joo GJ, Kim HW, Ha K, Recknagel F. 2001. Prediction and elucidation of phytoplankton dynamics in the Nakdong River (Korea) by means of a recurrent artificial neural network. Ecol Modelling 146: 115-129.

Jeong KS, Kim DK, Joo GJ. 2007a. Delayed influence of dam storage and discharge on the determination of seasonal proliferations of *Microcystis aeruginosa* and *Stephanodiscus hantzschii* in a regulated river system of the lower Nakdong River (South Korea). Water Res 41: 1269-1279.

Jeong KS, Kim DK, Whigham P, Joo GJ. 2003. Modelling *Microcystis aeruginosa* bloom dynamics in the Nakdong River by means of evolutionary computation and statistical approach. Ecol Modelling 161: 67-78.

Joo GJ, Jeong KS. 2005. Modelling community changes of cyanobacteria in a flow regulated river (the lower Nakdong River, S. Korea) by means of a Self-Organizing Map (SOM). *In* Modelling Community Structure in Freshwater Ecosystems (Lek S, Scardi M, Verdonschot PFM, Descy JP, Park YS, eds). Springer, Berlin, pp. 273-287.

Kang YT, Hyun KS. 1997. Modeling of water quality improvement by mass loading regulation in the Nakdong River basin. JKTSWT 5: 3-10.

Kim DK, Jeong KS, Whigham PA, Joo GJ. 2007. Winter diatom blooms in a regulated river in South Korea: explanations based on evolutionary computation. Freshwater Biol 52: 2021-2041.

Kim HW. 1999. Water quality, plankton community dynamics, and trophic regulation in the microbial food web by zooplankton in a hypertrophic river (Nakdong River, Korea). Dissertation, Pusan National University, Busan.

Kim HW, Chang KH, Jeong KS and Joo GJ. 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: 420-426.

Kim HW, Joo GJ. 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 HW, Joo GJ, Walz N. 2001. Zooplankton Dynamics in the hyper-eutrophic Nakdong River system (Korea) regulated by an estuary dam and side channels. Int Rev Hydrobiol 86: 127-143.

Kolmakov VI, Gaevskii NA, Ivanova EA, Dubovskaya OP, Gribovskaya IV, Kravchuk ES. 2002. Comparative analysis of ecophysiological characteristics of *Stephanodiscus hantzschii* Grun. in the periods of its bloom in recreational water bodies. Russ J Ecol 33: 97-103.

Lamouroux N, Souchon Y. 2002. Simple predictions of instream habitat model outputs for fish habitat guilds in large streams. Freshwater Biol 47: 1531-1542.

Lekka E, Kagalou I, Lazaridou-Dimitriadou M, Albanis T, Dakos V, Lambropoulou D, Sakkas V. 2004. Assessment of the Water and Habitat Quality of a Mediterranean River (Kalamas, Epirus, Hellas), in Accordance with the EU Water Framework Directive. Acta hydrochim hydrobiol 32: 175-188.

Maheshwari BL, Walker KF, McMahon TA. 1995. Effects of regulation on the flow regime of the River Murray, Australia. Regul River Res Manage 10: 15-38.

Maier HR, Burch MD, Bormans M. 2001. Flow management strategies to control blooms of the cyanobacterium, *Anabaena circinalis*, in the River Murray at Morgan, South Australia. Regul River Res Manage 17: 637-650.

Muylaert K, Sabbe K. 1998. Spring phytoplankton assemblages in and around the maximum turbidity zone of the estuaries of the Elbe (Germany), the Schelde (Belgium/The Netherlands) and the Gironde (France). J Mar Syst 22: 133-149.

Park SB, Lee SK, Chang KH, Jeong KS, Joo GJ. 2002. The impact of Jangma (monsoon rainfall) on the changes of water quality in the lower Nakdong River (Mulgeum). Korean J Limnol 35: 161-170.

Rader RB, Belish TA. 1999. Influence of mild to severe flow alterations on invertebrates in three mountain streams. Regul River Res Manage 15: 353-363.

Reyjol Y, Lim P, Belaud A, Lek S. 2001. Modelling of microhabitat used by fish in natural and regulated flows in the river Garonne (France). Ecol Modelling 146: 131-142.

Scheffler W, Morabito G. 2003. Topical observations on centric diatoms (Bacillariophyceae, Centrales) of Lake Como (N. Italy). J Limnol 62: 47-60.

Schleiter IM, Borchardt D, Wagner R, Dapper T, Schmidt KD, Schmidt HH, Werner H. 1999. Modelling water quality, bioindication and population dynamics in lotic ecosystems using neural networks. Ecol Modelling 120: 271-286.

Stober QJ, Nakatani RE. 1992. Water quality and biota of the Columbia River system. In Water Quality in North American River Systems (Becker CD, Neitzel DA, eds). Battelle Press, Ohio, pp. 51-83.

Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res Appl 19: 397-441.

Wetzel RG, Likens GE. 1991. Limnological Analyses. Springer-Verlag, New York.

Zar JH. 1999. Biostatistical Analysis. Prentice-Hall, New Jersey.

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