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Longitudinal Gradients and Seasonal Dynamics of Nutrients, Organic Matter and Conductivity Along the Main Axis of Han-River

Kim, BitNa, Sang-Jae Lee, Jinwon Seo[1] and Kwang-Guk An*

(School of Bioscience and Biotechnology, Chungnam National University,
Daejeon 305-764, Korea
[1]Korea Institute of Water and Environment, Korea Water Resources Corporation,
Daejeon 305-730, Korea)

The purpose of the study was to evaluate spatial and temporal dynamics of nutrients (TN, TP), organic pollution (BOD, COD), and ionic dynamics (electrical conductivity, EC) in the North Han-River, South Han-River, and merged downriver using the dataset of 1998~2007, obtained from the MEK (Ministry of Environment, Korea). According to interannual nutrient analysis, TN varied slightly in the North Han-River and South Han-River, but decreased in the merged downriver along with BOD. Longitudinal analysis in the water quality showed that BOD, COD, and nutrients had linear decreasing trend along the main axis of headwater-to-downriver. Concentrations of TP and TN in the North Han-River averaged 26.97 μg L^{-1}, 1.696 mg L^{-1}, respectively, which were minimum in the three watersheds, followed by South Han-River and then the merged downriver in order. Ratios of TN : TP in the watersheds were >40 in all the sites, indicating that nitrogen may be enough for periphyton or phytoplankton growth and phosphorus may be limited partially. After the North Han-River water is merged with South Han-River, the concentrations of BOD, COD, TN, and TP were similar to the values of S6~S7, respectively or a little bit higher, but increased abruptly in Site M4 (Fig. 3). Thus, mean values of all the water quality parameters in the reach of M4~M7 sites were greater than any other sites. Seasonal data analysis indicated that BOD and EC in the downstream (S3~S7) was greater in the premonsoon than two seasons of the monsoon and postmonsoon, and no significant differences in BOD between the three seasons were found in the upstream (S1~S2). Empirical models of COD in the merged downriver was predicted (R^2=0.87, $p<0.01$, slope= 0.84, intercept =−1.28) well by EC. These results suggest that EC to be measured easily in the field may be used for estimations of nutrients and organic matter pollutions in the merged downriver and these linear models are cost-effective for the monitoring of the parameters.

Key words : River water quality, Han-River watershed, nutrient, empirical model, longitudinal gradient

INTRODUCTION

The Han-River watershed is located in the middle of Korean peninsula, and the river length and the watershed area are 459.3 km and 3.5×10^4 km^2, respectively (Seoul City, 2007). The watershed is divided into two of North Han-River and

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* Corresponding author: Tel: +82-42-821-6408, Fax: +82-42-822-9690, E-mail: kgan@cnu.ac.kr

South Han-River, merged into one in the Yangsu-Ri, and the waters come into the Paldang Reservoir, which is main source of drinking water for citizens in Seoul City (Ministry of Construction & Transportation, 2004). The two watersheds are mainly surrounded by forests and agricultural land (rice paddy), so the pollution in the rivers is not intense. The 85 km downrivers from Paldang Reservoir, however, are surrounded by dense population urban region. Thus, large spatial heterogeneity in the water quality are expected in the river.

Previous studies reported that water quality of the downriver from the Paldang Dam is widely influenced by effluents of various wastewater disposal plants and intense residental-commercial area (Kim *et al.*, 2005). Thus, BOD and COD levels have been increased abruptly in the downriver reach (Kim *et al.*, 1995) from the Paldang Reservoir and nutrient pollutions, based on nitrogen and phosphorus, were severe in the downriver. In contrast, water quality North Han-River and South Han-River, which are located in the upstream region from the Paldang Reservoir, were better than the downriver. Shin *et al.* (2000) pointed out that these longitudinal differences in the water quality are closely associated with land-use pattern in the surrounding river. Such heterogeneous spatial variations in water quality along the river axis are similar to some rivers in foreign countries (Faulkner *et al.*, 2000; Baker *et al.*, 2004; Mancini *et al.*, 2004). Serial impoundment systems along the main axis of the river in Han-River watershed may make the river system more confuse to understand. It is known that nutrients and suspended solids in dendritic dam reservoirs decrease downlake along the main-axis of the reservoir. In case of Han-River watersheds, such hypothesis may be modified due to the large variations in the magnitude of point sources and landuse patterns along the rivers and dam reservoirs.

Furthermore, seasonal dynamics of nutrients, organic matter and EC in Asian region are difficult to determine the water quality pattern along the river (An, 2000b). One third of total annual precipitations occured in the short monsoon season of July～August and this features resulted in dynamics of chemical water quality in Korean rivers and dam reservoirs (An and Jones, 2000; An, 2001; An and Kim, 2003; Kim and Kim, 2004). The temporal dynamics in the water quality are widely reported in the previous numerous researches of Han-River watersheds (Huh *et al.*, 1999; Yoo, 2002; Jeong *et al.*, 2004; Kim *et al.*, 2007). Also, the time, volume, and the discharge duration from each serial impoundment dam are different due to maximal levels and the storage capacity of the water and water quality may have a time-lag phenomenon along the main axis of the river. These morphological and hydrological features would increase the spatial heterogeneity of water quality in the Han-River Watershed. For these reasons, it is necessary to do research on water quality dynamics in relation to seasonal rainfall distribution, spatial heterogeneity, and point/non-point sources (An and Shin, 2005), especially in the spatially dynamic Han-River watershed. The conservation and protection strategies of sustainable water resources are imminent in the Han River watershed (Seo *et al.*, 2007) and thus numerous chemical measurements and biological surveys have been conducted site-specifically in the watershed. However, still little is known about how the river water quality varies along the main axis of the headwater-to-downriver and over seasons in the Han River Watershed.

In this study, we determined the longitudinal patterns of EC, nutrients (TN, TP), COD, and BOD along the main axis of the Han-River and also analyzed interannual and seasonal patterns of water quality in relation to the monsoon rainfall distributions.

MATERIALS AND METHODS

1. Descriptions of sampling watersheds and sites

Three major watersheds (North Han-River, South Han-River, and Merged downriver) from South and North Han-River were selected for sampling regions and seven sites were choosen from each watershed (Fig. 1).

The North Han-River watershed is characterized as high proportion of forests and agricultural lands with low population density in the landuse and the river slope is relatively steep. The watershed contains five serial impoundments dams such as Hwacheon, Chunchon, Soyang, Euam, and Chungpyung dam reservoirs along the river. The South Han-River watershed is mainly composed of agricultural lands and forests are rare, while the geology is featured as limestone and granite rocks. Thus, agricultural activities are intense in

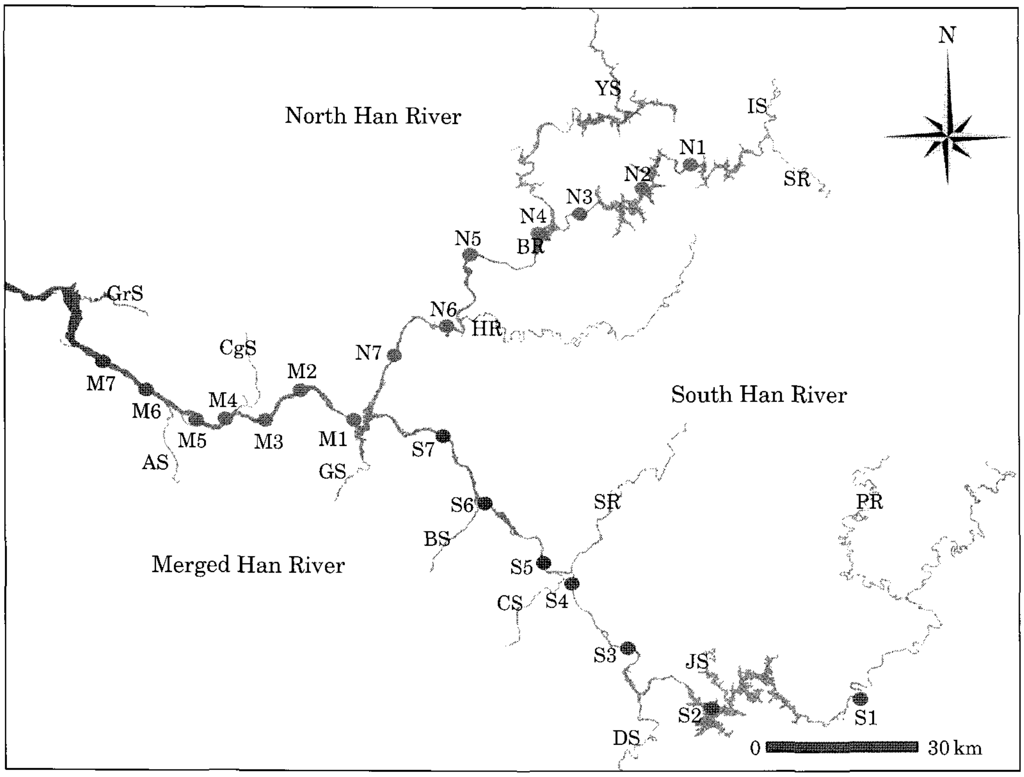

Fig. 1. Map showing the sampling sites in Han-River watersheds (GrS=Gokreung stream, AS=Anyang stream, CgS =Chunggye stream, GS=Gyeongan stream, HR=Hongcheon river, BR=Bukhan river, SR=Soyang river, IS=Inbuk stream, YS=Yangguseo stream, BS=Bokha stream, SR=Seom river, CS=Chungmi stream, DS=Dal stream, JS= Jacheon stream, PR=Pyeongchang river).

South Han-River watershed containing Chungju Reservoir and the coral mines are scattered in the region. The merged downriver watershed is located in intense commercial urban area and extensive agricultural lands, and also is largely influenced by effluents from domestic and industrial wastewater disposal plants. For this reason, organic and nutrient pollutions in the merged downrivers are severe, compared to the North and South Han-River (Park *et al.*, 1995).

The sampling sites of North Han-River watershed are as follows (Fig. 1): N1=Nambok-ri, Inje-ep Inje-gun Kwangwon-do, N2=Cheonjeon-ri Sinbok-ep Chunchon-si Kwangwon-do, N3=Cheonjeon-ri Sinbok-ep Chunjeon-si Kwangwon-do, N4 =Euam-ri Sindong-myeon Chunjeon-si Kwangwon-do, N5=Anbo-ri Seo-myeon, Chunjeon-si Kwangwon-do, N6=Gosung-ri OeSeo-myeon Gapyung-gun Gyeonggi-do and N7=Daesung-ri OeSeo-myeon Gapyung-gun Gyeonggi-do. The sampling sites of South Han-River watershed are as follows (Fig. 1): S1=Gadae-ri Gagok-myeon Danyang-gun Chungcheongbok-do, S2=Jongmin-dong Chungju-si, Chungcheongbok-do, S3=Mokgye-ri Gagum-myeon Chungju-si Chungcheongbok-do, S4 = Buron-myeon Wonju-si Kwangwon-do, S5=Jeokgeum-ri Gangcheon-myeon Yeoju-gun Gyeonggi-do, S6=Hongmoon-ri Yeoju-eup Yeoju-gun Gyeonggi-do and S7=Gyopyeong-ri Gangsang-myeon Yangpyeong-gun Gyeonggi-do. The sampling sites of merged downriver watershed are as follows (Fig. 1): M1=Neungnae-ri Joan-myeon Namyangju-si Gyeonggi-do, M2= Topyeong-dong Guri-si Gyeonggi-do, M3=Shincheon-dong Songpa-gu Seoul-si, M4=Sungsu-dong Sungdong-gu Seoul-si, M5=Bon-dong Dongjak-gu Seoul-si, M6=Gayang-dong Gangseo-gu Seoul-si and M7=Singuk-ri Gocheon-myeon Kimpo-si. The overall number of sampling sites is 21 in the three watersheds.

2. Water quality data and some parameters

Water quality parameters used in this study were biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and electric conductivity (EC) sampled during 1998 ~ 2007 and the dataset were obtained from the MEK (Ministry of Environment, Korea). Data were analyzed in relation to longitudinal patterns along the main axis of the river and long-term interannual patterns over 10 years. Also, seasonal patterns were analyzed over the 12 months and the seasons were divided into three seasons of premonsoon (May ~ June), during monsoon (July ~ August), and postmonsoon (September ~ October) to determine the monsoon effect on the water quality. The simple linear regression analysis and correlation analysis were conducted by SPSS program.

RESULTS AND DISCUSSION

In the Han-River watershed, annual precipitation during 1998 ~ 2007 averaged 1,486 mm and summer rainfall was 803 mm which was 54% of the total (Fig. 2). During the study, 2001 was drought year (1,090 mm) and 2003 was flooding year (1,866 mm). Previous studies (An, 2000a, b; An and Jones, 2000; An and Kim, 2003) pointed out that the interannual difference in the rainfall is closely associated with chemical water quality dynamics. This phenomenon, however, was not evident in the watersheds of North Han-River and South Han-River, but was largely influenced in merged downriver watershed (Fig. 2). Values of BOD in North Han-River and South Han-River averaged 1.0 mg L^{-1} and 1.2 mg L^{-1}, respectively and varied between 0.9 and 1.5 mg L^{-1} (Fig. 2), indicating low interannaul variation regardless of years. In contrast, BOD and COD in the merged Han-River averaged 2.6 and 4.7 mg L^{-1}, respectively during 10 years (Fig. 2). In the merged downrivers, COD values were maximum in the drought year (2001) and minimum in the wet year

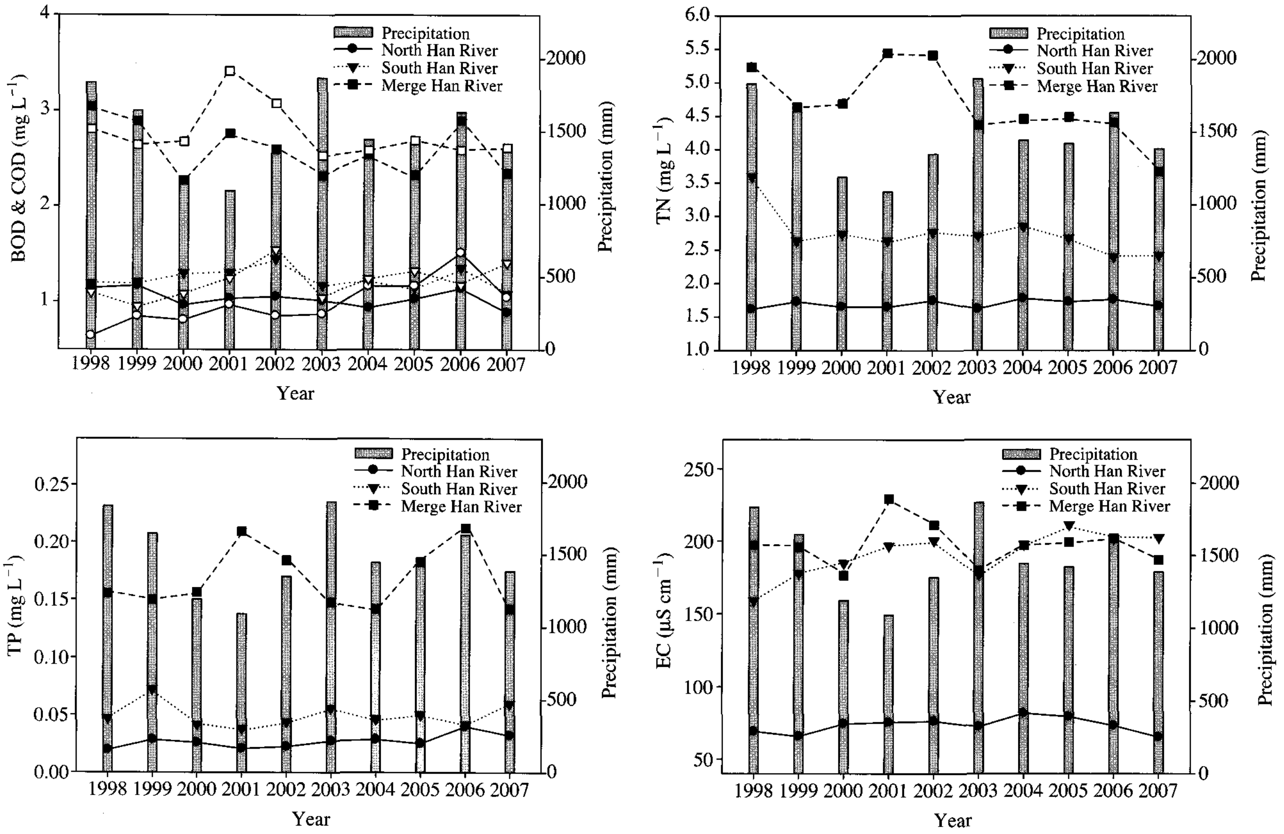

Fig. 2. Interannual vatiation of biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphrous (TP), electrical conductivity (EC) in relation to annual precipitation (dark triangle/square/circle=BOD; open triangle/square/circle=COD).

(2003), indicating that rainwater diluted the river water in the flood year. Similarly, values in TP and EC were highest 0.212 mg L^{-1} as TP; 230 μS cm^{-1} as EC in the drought, respectively (Fig. 2). Concentrations of TN declined from the 1998 to 2007, and this may be due to an increased removal efficiency of nitrogen from domestic and industrial wastewater disposal plants.

Values of BOD, COD, and nutrients (TN, TP) showed typical longitudinal gradients from the upstream to downstream (Fig. 3). Values of TN showed 1.97 mg L^{-1}, 2.75 mg L^{-1} and 4.68 mg L^{-1} in the North Han-River, South Han-River, and merged downriver, respectively. Values of TP showed 0.027 mg L^{-1}, 0.050 mg L^{-1} and 0.170 mg L^{-1} in the North Han-River, South Han-River, and merged downriver, respectively. The low values of phosphorus in the North Han-River watershed may be a result of forest dominance in the landuse as well as continuous sedimentation processes by serial impoundment dams such as Hwacheon, Chunchon, Soyang, Euam, and Chungpyung reservoirs along the river. In case of nitrogen, it may be enough for periphyton or phytoplankton growth and phosphorus may be limited partially. High nitrogen in the watershed may be associated with high dissolved form (nitrate-N) from rather than phosphorus with high proportion of particulate forms sedimented easily out from the water column (Cooke and Williams, 1973; Happer, 1992). In the North Han-River and South Han-River, BOD, COD, TN, and TP showed slight difference between N1 and N7 and between S1 and S7, respectively, but showed large differences by 2~4 fold between M1 and M7 site (Fig. 3). After the North Han-River water is merged with South Han-River, the concentrations of BOD, COD, TN, and TP were similar to the values of S6~S7, respectively or a little bit higher, but increased abruptly in Site M4 (Fig. 3). Thus, mean values of all the water quality parameters in the reach of M4~M7 sites were greater than any other sites.

The abrupt degradation in the downriver water quality is attributed to massive discharges of organic matter and nutrients by effluents from tributary Chunggye Stream and Anyang Stream. In the mean time, EC did not showed longitudinal gradients from N1 to N7 and S1 to S7 (Fig. 3). However, there were downriver decreasing trend of EC along the longitudinal gradients from M1 to M7 (Fig. 3). Spatial gradients analysis indicated that water quality, based on EC, BOD, COD,

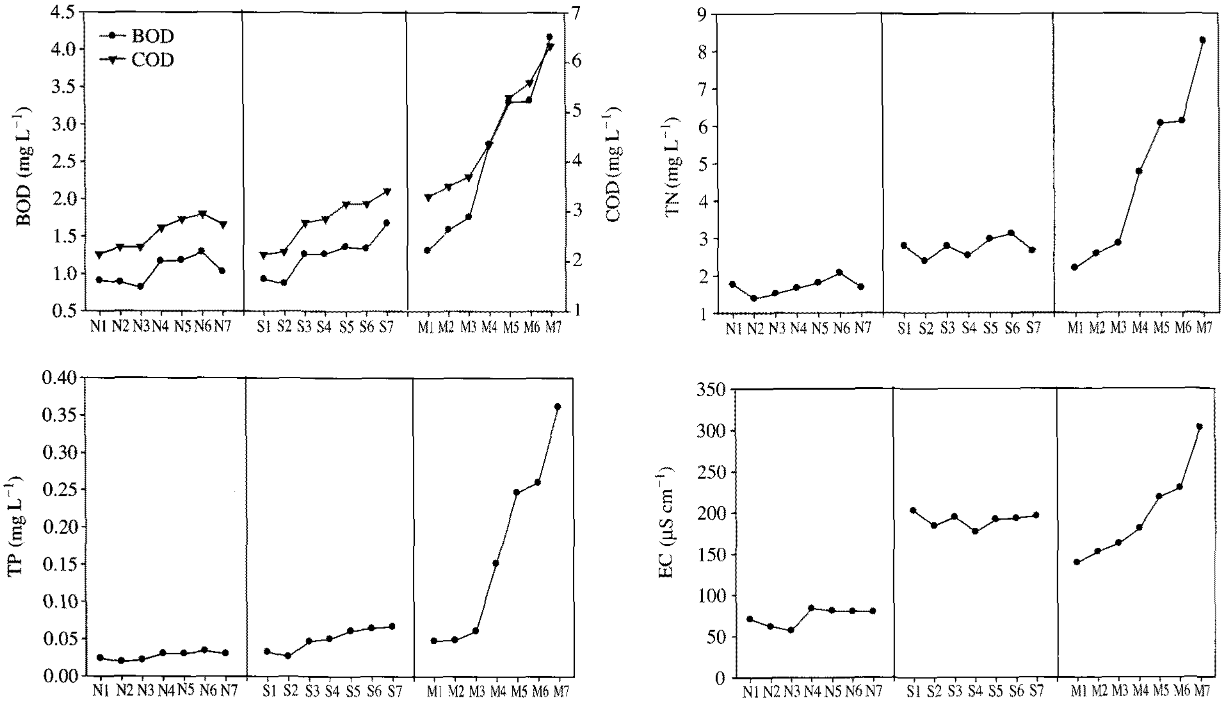

Fig. 3. Longitudinal variations in BOD, COD, TN, TP, and EC in the North Han-River (N1~N7), South Han-River (S1~S7), and the merged downriver (M1~M7). Each data averaged values during 1998~2007.

and nutrients, was greatest in North Han-River, followed by South Han-River, and then the merged downriver reach, and that severe degradations of water quality occurred in M4 site, which is influenced by sewage effluents from Chunggye Stream (by the polluted water before the restoration).

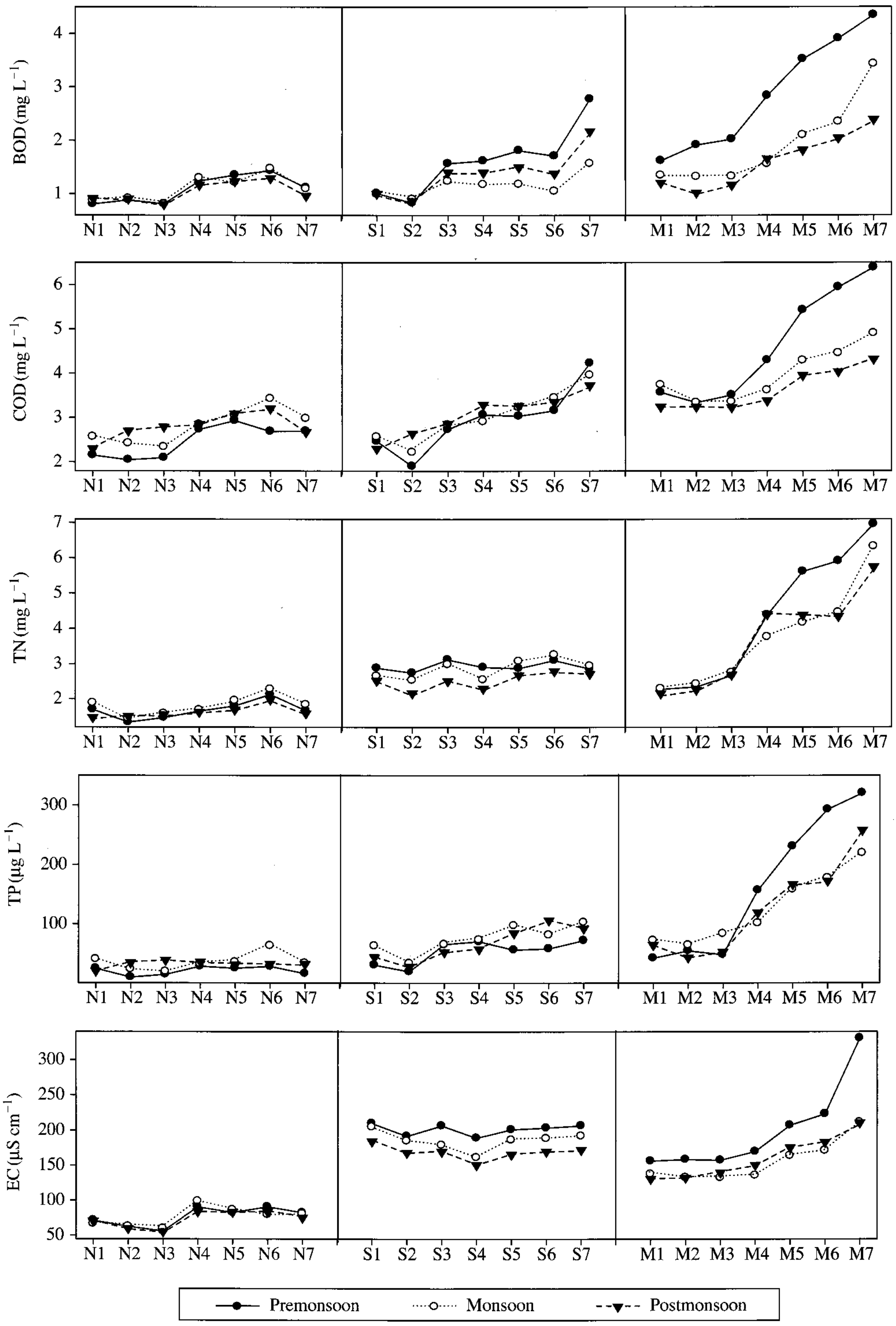

Fig. 4. Water quality in the North Han-River (N1~N7), South Han-River (S1~S7), and the merged downriver (M1~M7) during the premonsoon (May~June), monsoon (July~August) and postmonsoon (September~October).

Also, effluents from Jungran Stream between M4 and M5 may one of the most influencial pollutants in the merged downstream, thus largest difference in the water quality between the sites occurred in the locations. One of the problems in the effluents is that the water comes from two domestic wastewater disposal plants in the middle of Jungrang Stream (Kim and Han, 2005). Lee and Byun (2001) emphasized that the effluents are waters by only primary treatment and nutrients and organic matter concentrations are high. The point source seems to contribute the large increases in TP and TN along with BOD and COD between M4 and M5 in the merged downriver.

Seasonal monsoon rain during summer contributed largely in the merged downstream regions rather than North Han-River and South Han-River watersheds. As shown in Fig. 4, In the North Han-River watershed, there were no significant differences ($p > 0.05$) in BOD, COD, TN, TP, and EC

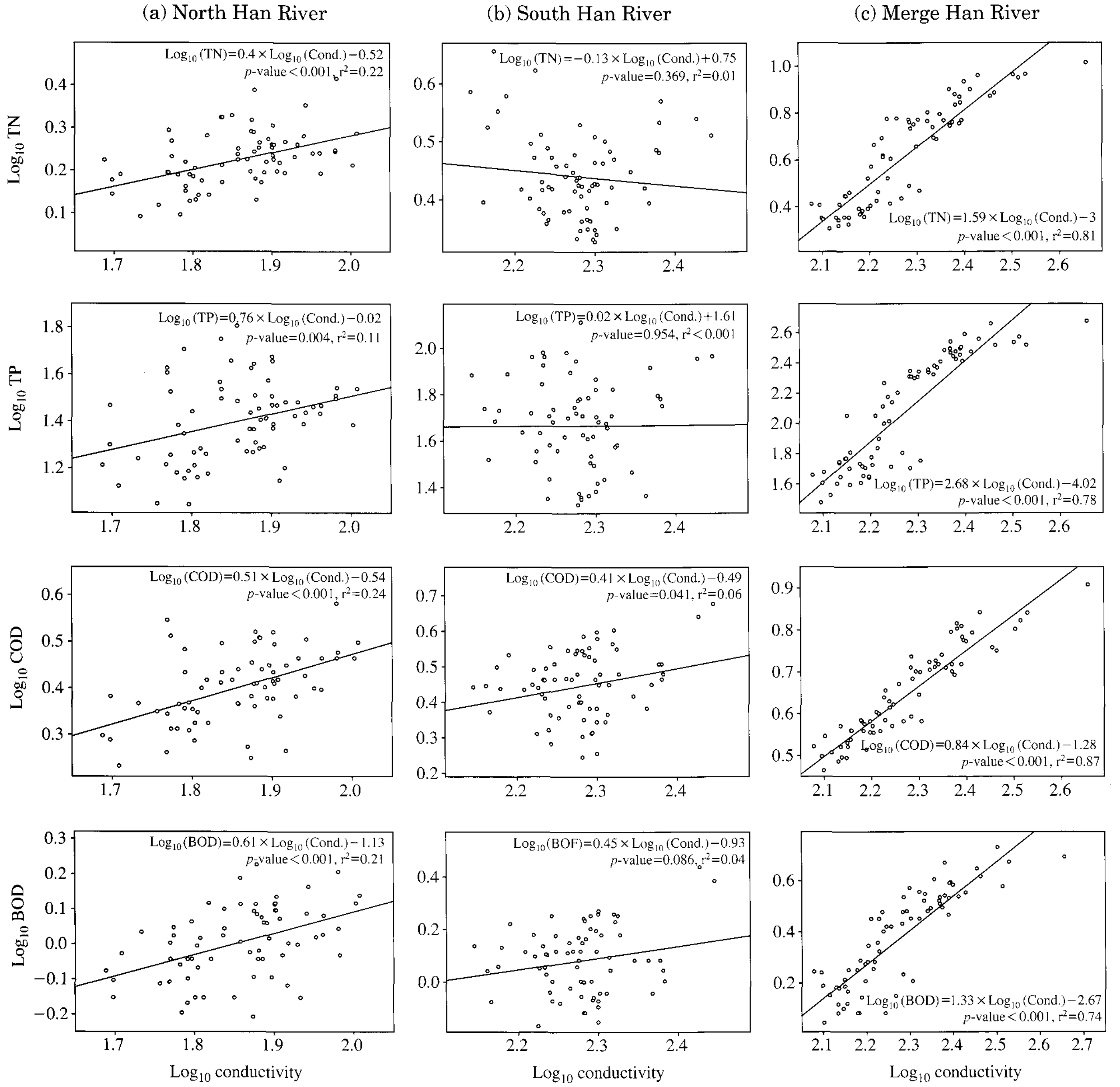

Fig. 5. Empirical linear models of Log_{10} TN vs Log_{10} COND, Log_{10} TP vs Log_{10} COND, Log_{10} COD vs Log_{10} COND, and Log_{10} COD vs Log_{10} COND in the three different watersheds.

between three seasons of premonsoon, monsoon and postmonsoon (Fig. 4). In the mean time, South Han-River watershed, there were no significant differences ($p > 0.05$) in COD, TN, TP between three seasons of premonsoon, monsoon and postmonsoon. In contrast, BOD and EC in the downstream (S3 ~ S7) was greater in the premonsoon than two seasons of the monsoon and postmonsoon, and no significant differences in BOD between the three seasons were found in the upstream (S1 ~ S2, Fig. 4). In the merged downriver watershed, there were no significant differences ($p > 0.05$) in COD, TN, TP between three seasons of premonsoon, monsoon and postmonsoon (Fig. 4). In contrast, BOD and EC was greater in the premonsoon than two seasons of the monsoon and postmonsoon (Fig. 4). The magnitude in the dilution of river water by rain water was most pronounced in the downriver of the merged watershed. These results indicate that river water quality, based on BOD, COD, TN and TP, was most severe in the premonsoon and the severely polluted water was diluted by 30 ~ 50% during the monsoon, thus no big differences in the water quality were found between monsoon and postmonsoon, as shown in the merged downriver sites (M1 ~ M7).

Empirical models of log-trans formed TN, TP, COD, and BOD against EC were developed in the three different watersheds because EC is easily measured in the field (Fig. 5). Simple linear models of $\mathrm{Log_{10}}$ TN vs $\mathrm{Log_{10}}$ COND, $\mathrm{Log_{10}}$ TP vs $\mathrm{Log_{10}}$ COND, $\mathrm{Log_{10}}$ COD vs $\mathrm{Log_{10}}$ COND, and $\mathrm{Log_{10}}$ COD vs $\mathrm{Log_{10}}$ COND in the South Han-River watershed showed low regression coefficients (R^2) of < 0.10, partially the values were statistically significant in the analysis (Fig. 5). The regression slopes ranged between 0.02 and 0.45 (n=70), indicating low slopes in the South Han-River watershed (Fig. 5). In the North Han-River watershed, variation of TN, COD and BOD was explained 21 ~ 24% by log-trans EC and the slopes were greater than those of South Han-River watershed. In the mean time, linear model of $\mathrm{Log_{10}}$ TP vs $\mathrm{Log_{10}}$ COND showed low regression coefficients ($R^2 = 0.11$, slope=0.76, intercept=−0.22). In contrast, water quality of TN, TP, BOD, and COD in the merged downriver was predicted well by EC. The regression equations in the merged downriver are as follows:

$\mathrm{Log_{10}\ TN = 1.59\ Log_{10}\ COND - 3.00}$
($R^2 = 0.81, p < 0.01$)
$\mathrm{Log_{10}\ TP = 2.68\ Log_{10}\ COND - 4.02}$
($R^2 = 0.78, p < 0.01$)
$\mathrm{Log_{10}\ COD = 0.84\ Log_{10}\ COND - 1.28}$
($R^2 = 0.87, p < 0.01$)
$\mathrm{Log_{10}\ BOD = 1.33\ Log_{10}\ COND - 2.67}$
($R^2 = 0.74, p < 0.01$)

As shown in the above equations, 87% in the variation of COD was explained by EC, while 81% in the variation of TN was explained by EC (Fig. 5). These results suggest that EC to be measured easily in the field may be used for estimations of TN, TP, COD, and BOD in the merged downriver and these linear models may be cost-effective for the monitoring of the parameters.

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