Overview and application of the National Aquatic Ecological Monitoring Program (NAEMP) in Korea

Sang-Woo Lee[1], Soon-Jin Hwang[1]*, Jae-Kwan Lee[2], Dong-Il Jung[3], Yeon-Jae Park[4] and Ji-Tae Kim[5]

[1] Department of Environmental Science, Konkuk University, Seoul 143-701, Republic of Korea
[2] Nakdong River Research Center, The National Institute of Environmental Research, Goryong 717-807, Republic of Korea
[3] Water Environment Research Department, The National Institute of Environmental Research, Incheon 404-170, Republic of Korea
[4] Department of Environmental Engineering, University of Seoul, Seoul 130-743, Republic of Korea
[5] Department of Environmental Energy Systems Engineering, Kyonggi University, Suwon 443-760, Republic of Korea

Abstract – This paper provides an overview of the development and application of the National Aquatic Ecological Monitoring Program (NAEMP) in Korea, which uses biological and habitat–riparian criteria for river/stream and watershed management. Development of NAEMP began in 2003, with recognition by the Korean Ministry of Environment (MOE) of the limitations of applying chemical parameters (*e.g.*, biochemical oxygen demand (BOD)) as the principal targets of water environment management. Ecosystem health criteria under NAEMP were developed from 2003 to 2006. Candidate sites for monitoring were also screened and established across the country. NAEMP was implemented in 2007, and since then a standard protocol of nationwide monitoring based on multi-criteria has been implemented to assess the ecological condition of rivers and streams. The monitoring results indicate that many Korean rivers and streams are severely degraded, with biological conditions that are much worse than their water chemistry suggests. In 2009, 24% of rivers and streams were in classes C (Fair) and D (Poor) for BOD, but more than 71, 53, and 27% were categorized as Fair to Poor according to fish, diatom, and benthic macroinvertebrate assemblages, respectively. NAEMP is promising in that the results have already had great impacts on policy making and scientific research relevant to lotic water environment and watershed management in Korea. In the future, NAEMP results will be used to develop more aggressive regulations for the preservation and restoration of rivers/streams, riparian buffer areas and watersheds. Another future aim of the NAEMP is to develop aquatic ecological modeling based on the monitoring results.

Key words: NAEMP / river and stream / ecosystem health / criteria / watershed management

Introduction

Water quality degradation due to intense land use and urbanization has been a focal area in aquatic system research, particularly river management, for several decades. Many studies have reported that the land use types and patterns within a watershed determine the characteristics of human activities, which in turn determine the anthropogenic substances carried into river systems (Omernik *et al.*, 1981; Lenat and Crawford, 1994; Bolstad and Swank, 1997; Gburek and Folmar, 1999; Liu *et al.*, 2000; Tong and Chen, 2002; Lee *et al.*, 2009). Moreover, land uses within a watershed can impact various intrinsic attributes of river systems, including hydrological, geomorphological, chemical, and biological aspects (Omernik *et al.*, 1981; Osborne and Wiley, 1988; Richards *et al.*, 1993; Richards *et al.*, 1996; Allan *et al.*, 1997).

In many countries, chemical parameters such as dissolved oxygen (DO), pH, biochemical oxygen demand (BOD), chemical oxygen demand, total nitrogen (TN), and total phosphorous (TP) have served as the main criteria for determining river conditions and managing aquatic ecosystem resources. Korea also used chemical criteria to develop its initial policies and regulations related to river water quality. The Environment Preservation Law (1978) in Korea categorized river water quality into five classes based on BOD, pH, DO, and SS (suspended solids).

Water quality programs targeting chemical criteria alone have been criticized as lacking consideration of

*Corresponding author: sjhwang@konkuk.ac.kr

the whole ecosystem (Davis and Simon, 1995; McCarron and Frydenborg, 1997). The chemical approach largely ignores the biological assemblages and their habitats. Aquatic biota, responding in complex and dynamic ways, reflect long-term, cumulative effects of various anthropogenic disturbances caused not only by nutrient enrichment and toxic chemicals but also by habitat and hydrological alterations (Karr and Chu, 1999), and thus aquatic biota are crucial components and indicators of ecosystem health (US EPA, 2002).

Recently, many studies have reported biological criteria and assessments for evaluation of the ecological condition of streams (Davies and Jackson, 2006; Hering *et al.*, 2006; Stoddard *et al.*, 2008; Waite *et al.*, 2008; Carlisle *et al.*, 2009). Various biological metrics, including individual and aggregated indices of algae, macrophytes, macroinvertebrates, and fish, have been proposed for various spatial extents, mostly in North America and Europe (Osborne and Suárez-Seoane, 2002; Hering *et al.*, 2006; Pont *et al.*, 2006; Johnson *et al.*, 2007; Ode *et al.*, 2008; Stoddard *et al.*, 2008). Although uncertainties remain in applying these metrics in ecological regions and spatial scales that differ from those for which the metrics were developed and verified (Kelly *et al.*, 2009; Nõges *et al.*, 2009), assessments of ecological status using biological indices and habitat condition have become drivers of water management and restoration practices.

This paper provides an overview of the Korean National Aquatic Ecological Monitoring Program (NAEMP) and the applications of this program, which uses biological and habitat criteria. The paper also describes some key findings and experiences of the monitoring program development process. The annual NAEMP reports have had significant impacts in various areas, including river water management policies, regulations, restoration plans, and land use planning in Korea. NAEMP researchers have developed biological criteria for benthic diatoms, macroinvertebrates, and fish, as well as metrics for habitat quality. NAEMP is a comprehensive program that assesses river ecological condition including water chemistry, biological assemblages, habitat quality, and land uses surrounding rivers. The program also maintains a web-based database to provide monitoring results to the public. To our knowledge, few other countries have developed and implemented a nationwide monitoring program with multi-biological criteria to assess the environmental conditions of lotic ecosystems.

NAEMP in Korea

Target river systems

South Korea is located within 127°30'E, 37°00'N and occupies about 109 027 km², covering the whole southern half of the Korean Peninsula. Approximately two-thirds of the annual precipitation of 1324 mm is concentrated in the summer (June through September). Thus, seasonal precipitation and water flow levels fluctuate widely, and during winter and spring, streams often suffer from drought. Flooding in summer and drought in winter and spring are becoming increasingly severe under recent erratic climate variations (KMA, 2008). The annual average temperature for the last five years (2006–2010) was 12.8 °C, with monthly averages ranging from the lowest of -12.8 °C in January to the highest of 29.3 °C in August.

Five major rivers, the Han, Geum, Nakdong, Youngsan, and Seomjin rivers, and their independent tributaries and small streams encompass the entire country. The Youngsan and Seomjin rivers are usually treated as one river system (Youngsan–Seomjin River) because their watersheds are closely located. Among the five major rivers, the Han River has the largest river basin, occupying approximately a quarter of the country. The east side of the country is mountainous, with less disturbed watersheds covered by dense pine, oak, and mixed forests. Short, small independent streams with relatively steep grades are found in the eastern mountainous areas. These small independent streams flow toward the East Sea, while most river systems and streams in western and southwestern areas flow toward the Yellow (West) Sea. Seasonal fluctuations in water levels in short, independent streams in the eastern areas are particularly extreme because of the steep slopes and low groundwater levels.

Biological criteria approach for water management practice

Since the late 1990s, aquatic ecologists and experts in the public domain have increasingly voiced concern regarding the ecological status of Korean rivers. Only relatively recently has the Korean government paid close attention to ecological integrity as a part of water management policy (MOE/NIER, 2006). With the adoption of the concept of ecosystem health to express the structural and functional quality of aquatic ecosystems for water management practices, the Ministry of Environment (MOE) in Korea guided a planning study in 2003. The final report of this planning study stressed the establishment of nationwide biological criteria to incorporate the concept of ecosystem health into water quality programs and management practices (NIER, 2003). At that time, biological characteristics of aquatic ecosystems had never been assessed nationally in Korea. Although some biological aspects of streams had been assessed in individual research cases, overall management standards and criteria, as well as restoration practices, led by government agencies relied solely on chemical criteria, due to the lack of biological information for target streams (NIER, 2003).

Biological criteria have been widely adopted to evaluate the ecological condition of running waters (US EPA, 1990; Barbour *et al.*, 1999). This approach has some considerable benefits compared to conventional methods (*i.e.*, chemical criteria analysis) for evaluating water quality. For example, biological approaches can detect factors such as low-level and non-point source pollutants

(Barbour *et al.*, 1999), physical habitat alteration (Kutka and Richards, 1996; Nerbonne and Vondracek, 2001), and long-term ecosystem effects of anthropogenic influences (Barbour *et al.*, 1999). Biological criteria can be considered as ecological benchmarks, and various biological indices are assumed to be sensitive to environmental changes and disturbances induced mostly by humans (Davis and Simon, 1995; Simon, 1999). According to the US EPA (1990), biological criteria expressed narratively and/or numerically describe the reference biological integrity of aquatic communities inhabiting waters. Biological criteria include a wide range of indices describing the variability and condition of biological communities in streams (Simon, 2000). The most commonly used biological criteria are diversity indices, univariate indices, the floristic quality index, the index of well-being, and population and composition indices of benthic diatoms, macroinvertebrates and fish, and biological integrity (Gammon, 1976; Karr, 1981; Hilsenhoff, 1982; Nielsen and Johnson, 1983; Washington, 1984; Karr *et al.*, 1986; Swink and Wilhelm, 1994; DeShon, 1995; Stewart *et al.*, 1999).

Development of NAEMP

Brief history of the development of NAEMP

Accompanying trends in the United States (US EPA, 1990) and in European countries (EEA, 1996), the limits and pitfalls of chemically oriented criteria for water management practices have been increasingly recognized in Korea since the 1990s. This increasing awareness spurred the Korean government to change the framework of its water management policy in 2000, the beginning of the new millennium. The first step was to establish a nationwide advisory council to provide advice on the comprehensive assessment of water quality. This temporary 2-year council conducted a benchmark planning study to construct a new framework for a national water quality program. One of the most striking results was to achieve consensus on the adoption of biocriteria for the water management program. The concept of biocriteria for water management practices was later incorporated into the master plan for water environment management (MOE/NIER, 2006). Based on this master plan, the 1978 Korean water quality standard was amended. Chemical criteria were subdivided (from a five-class to seven-class standard) and biological criteria were newly added (four classes of narrative description). The original Water Quality Preservation Law was renamed the Law of Water Quality and Aquatic Ecosystem Preservation in 2007.

Following the planning study, a 3-year project (2003–2006) was initiated to develop bioassessment methods. Key groups of focus were assemblages of the main constituents of the stream food chain: benthic epilithic diatoms, macroinvertebrates, and fishes. These three indicators were studied because each biological assemblage responds differentially to broad-scale environmental factors (Barbour *et al.*, 1999; UNESCO, 2004). Thus,

bioassessment using assemblages for different trophic levels can be used to closely evaluate scale-dependent ecological phenomena (Levin, 1992) and the results for the different trophic levels can complement one another (Passy *et al.*, 2004). Because of these advantages, the three levels of bioindicators were selected as biocriteria, and tools for their quantitative assessments were developed. Although various biota have been proposed as bioassessment tools, such as in the "Rapid Bioassessment Protocol" (Barbour *et al.*, 1999), it is unusual to assess three different biological assemblages and incorporate them simultaneously into an official monitoring program. Next, the value of aquatic plants (macrophytes) to the bioassessment was proposed, and an assessment method was independently developed based on the concept of vegetation naturalness (MOE/NIER, 2008).

To develop the bioassessment tools, 119 streams (including 39 reference streams) across the country were surveyed for the three levels of biota and their environmental condition. Information relating to taxonomic composition and abundance, indicator species, and the ecological characteristics of each biotic assemblage, as well as abiotic variables including nutrients and organic matter, were obtained from the study streams. The theoretical and practical grounds for the bioassessment protocols developed in this study were not new, but protocols were either modified or amended based on those already proposed and developed by other researchers. For example, the framework of the saprobic index (Zelinka and Marvan, 1961) was adopted for macroinvertebrate and diatom assemblages. Indices for these two biota were based on the abundance of observed taxa, their sensitivity or saprobic values to pollution (*i.e.*, nutrients or organic matter), and their indicator values or weighting factors in terms of occurrence of each taxon in pollution gradients. The values of pollution sensitivity and indicator (or weighting) factors in the original models were amended for taxa residing in the studied Korean streams. The concept of biological integrity (Karr, 1981) was adopted for fish, and the number of metric components and their categorization, representing ecological properties, were modified to reflect environmental conditions and fish species in Korea. Developed assessment methods were intercalibrated among major rivers across the country, and the protocol has been amended on a yearly basis to address any questions and problems.

The numerical criteria were developed with tiered use of aquatic life (benthic diatoms, macroinvertebrates, and fish) and habitat quality. Finally, a four-class system describing the condition of the criteria was established: Class A (Excellent), Class B (Good), Class C (Fair), and Class D (Poor).

Establishing the monitoring network and operation plan for NAEMP

NAEMP was designed to cover the whole country (five major river basins) for assessment of biocriteria as well as

Table 1. Establishment of the NAEMP monitoring network in Korea.

Watersheds	Number of candidate monitoring sites	Number of surveyed sites in each year				Target number of monitoring sites
		2007	2008	2009	2010	
Total	5711	540	600	720	800	1200 (110)[a]
Han River	1702	320	320	320	340	435 (40)
Nakdong River	1658	60	100	130	150	347 (30)
Geum River	1222	40	100	130	150	218 (20)
Youngsan–Seomjin River	1129	120	120	140	160	200 (20)

[a]Numbers in parentheses indicate reference sites.

Table 2. Operation and utility of NAEMP in Korea.

Parameters	Monitoring interval	Monitoring frequency	Geographic coverage	Implementation
a. Aquatic organism – benthic diatoms – macroinvertebrates – fish b. Habitat quality c. Physico-chemical parameters	Every year	Twice a year (spring and fall)	Entire country including watersheds of five major rivers (1200 sites including 110 reference sites)	– Evaluate biodiversity and ecological health – Provide basic information for restoration – Provide the results to the public

habitat criteria. The ultimate goal is to evaluate and monitor the ecosystem health of Korean rivers and streams. In the initial stages of developing the monitoring program, an important task was to select monitoring sites and establish the monitoring network.

In 2007, an independent study was initiated to screen possible monitoring sites including all streams and rivers longer than 10 km in Korea; these included all designated national and local rivers and small streams. In total, 3893 rivers and streams were surveyed. Every 5 or 10 km reach was segmented in each river/stream, and a list of 5711 potential monitoring sites was compiled. Researchers visited all reaches of the selected rivers/streams, and a suitable site in each reach was selected by considering four assessment variables: accessibility, representativeness, stability, and naturalness. The condition of each variable was simply divided into three levels (5, 3, and 1 points) with different weighting values. The evaluation scores summed for each site were listed for all 5711 sites, with the scores used to prioritize monitoring sites. Among all potential sites, pre-existing sites of the "National Water Quality Monitoring Network" and core representative points of the designated areas of water management (MOE/NIER, 2007) had first priority in the monitoring network.

For the NAEMP monitoring network, a total of 1200 sites were established, including 110 reference sites (Table 1). The first national-scale survey was initiated by the MOE/NIER in 2007. In the first year of bioassessment, only about half of the monitoring sites (540) were surveyed, due to a limited budget, but the number of monitored sites has increased by 60–100 sites every year.

NAEMP monitoring is conducted twice every year in two periods before and after the summer monsoon, *i.e.*, during spring (March–April) and fall

(September–October) as shown in Table 2. The program includes not only bioassessment but also habitat quality assessment. Investigation of physico-chemical water quality parameters and simple hydraulic parameters (water velocity, width, and depth) are also included in the program. Surveys of reference streams (sites) are emphasized because results from reference sites provide basic information for management practices, especially for the restoration of disturbed rivers/streams.

All monitoring results are analyzed and archived in a database. The calculation of numerical indices is set to perform automatically when an investigator inserts raw data, in order to avoid any miscalculations. The main results of the monitoring are published in reports, the database, and in geographic information system (GIS) maps every year. The database is utilized to extract and analyze various kinds of information, such as the status of biodiversity and the ecosystem health of lotic ecosystems and their spatio-temporal variation. The database is also used in the conservation and restoration of lotic systems or particular reaches, as necessary. For example, a large-scale restoration project, including four major rivers and their tributaries, has been planned and conducted throughout Korea since 2009. This mega-scale project aims not only to ecologically restore major river ecosystems but also to secure abundant water volumes and control floods to cope with climatic change. Sixteen weirs and large-scale dredging operations are being conducted in the mainstreams of large rivers. The negative effects of these particular works on lotic ecosystem structure and function, such as alterations to stream channel morphology and substrate composition, have been noted. NAEMP plays an important role in monitoring such projects; monitoring results have provided basic information for developing strategies related to biodiversity and ecosystem health restoration,

habitat mitigation, and the designation of core conservation areas. Monitoring results are also being used to incorporate strategies and goals for the restoration of target rivers/streams into the master plan of ecological restoration of urban rivers/streams, led by the MOE, Korea (MOE/NIER, 2008).

Developing biological and habitat criteria for NAEMP

Benthic diatoms

The use of freshwater diatoms in evaluating river/ stream ecosystems is quite recent in Korea, although the first report of Korean freshwater diatoms dates from the early 1900s (Skvortzow, 1929). The Civil War in Korea in the early 1950s (1950–1953) hindered research. In the 1960s, freshwater diatom studies resumed, led by Chung et al. (1965). A few groups of university researchers continued taxonomic studies and some related ecological studies. The first attempt to apply bioassessment to diatoms in Korea was by Chung (1987), who used the diatom assemblage index for organic pollution (DAIpo; Watanabe et al., 1990). DAIpo was based on indicator diatoms grouped in three categories according to organic saprobicity (saprophobic, indifferent, and saprophilic taxa). Thus, the main approach using DAIpo was to distinguish the status of organic pollution in studied rivers/ streams.

In the process of developing diatom criteria and assessment tools, a broader range of numerical indices (*cf*. Prygiel et al., 1999) was analyzed to find a tool appropriate to Korean lotic conditions. The trophic diatom index (TDI) (Kelly and Whitton, 1995) was selected as the best candidate because it was developed based on diatom sensitivity and occurrence in relation to a limiting nutrient (PO_4-P) in freshwater systems. The values of sensitivity and indicators given in the original TDI were tested with the diatoms occurring in a variety of Korean rivers and streams, and the values for major taxa were amended following the methods of Kelly and Whitton (1995). A comparative study using TDI showed that the results obtained from Korean lotic ecosystems using the original sensitivity and indicator values for the same diatom taxa found in Korea were considerably different from those obtained using amended values (Kim and Hwang, in preparation). Additionally, the correlation coefficients between amended TDI scores and water quality variables (*e.g.*, nutrients) were much higher than those between original TDI scores and water quality variables.

The environmental condition as evaluated by diatoms was classified into four classes (A: Excellent; B: Good; C: Fair; D: Poor), as described above. The range of TDI scores for Class A (Excellent) was established based on the scores obtained from the reference streams. Then, TDI scores were allocated to each class by comparing the scores with nutrients (PO_4-P and TP) and BOD concentrations. Detailed information on classifying the numerical criteria for diatoms was reported by Hwang et al. (2006).

Macroinvertebrates

The significance of biological surveillance using macroinvertebrates was recognized earlier than that for diatoms, and intensive efforts were made to apply and develop macroinvertebrate assessment methods in Korea. During the 1970s to 1980s, studies (*e.g.*, Wui, 1974; Lee, 1977; Wui et al., 1983; Oh and Chon, 1991) mainly directly applied the original methods of Šrámek-Hušek (1956), the Beck–Tsuda biotic index (Tsuda, 1964), the biotic score (Chandler, 1970; Hilsenhoff, 1977), and the trent biotic index (Woodiwiss, 1978).

The development of a numerical index for Korea was initiated by Yoon et al. (1992a, 1992b, 1992c) using the macroinvertebrates found in Korean rivers/streams. They proposed a Korea saprobic index (KSI), constructed following the method of Zelinka and Marvan (1961), and subsequently applied saprobic values and weighting factors of macroinvertebrate taxa to the index. Kong et al. (1995) improved the KSI by providing the index with representative taxonomic groups and their occurrences, and renamed it the Korean biotic index. However, these indices had application limitations because they used only diversity indices in deciding saprobic values and weighting factors (Won et al., 2006).

In the process of developing the macroinvertebrate criteria and assessment tools, the KSI was modified and improved following the German standard method (DIN 38410, 1990). The saprobic and weighting values were calculated based on data from 913 sites in Korean rivers and streams. Environmental condition was classified into four classes (A: Excellent; B: Good; C: Fair; D: Poor) based on the index scores. The range of KSI score for each class was established based on nonlinear regression using KSI scores and BOD concentrations. Detailed information on the classifying numerical criteria for macroinvertebrates has been provided by Won et al. (2006).

Fish

Taxonomic and related ecological studies focused on ichthyology in the 1990s, although the indicator species concept was well recognized for evaluating the conditions of aquatic environments in Korea. Since the introduction of the index of biotic integrity (IBI) by Karr (1981), an IBI-type model using fish assemblages has been adopted by many countries. The IBI concept was only recently introduced in Korea, having first been used by Yeom et al. (2000). Since then, the IBI model has been widely applied to many Korean rivers/streams (An et al., 2001; Kwon and An, 2006).

During the process of developing an assessment protocol, the IBI model was screened for characteristics of Korean lotic systems and their resident fish assemblages. The 12 metric components originally proposed by Karr (1981) were reduced to eight metrics after analysis of their properties according to the ecological characteristics of Korean fish assemblages. All eight metrics were scored based on stream order, and the summed score of all

Table 3. Ecological and chemical status of 720 sites of Korean rivers/streams (2009).

Parameters	No. of sites in Excellent (%)	No. of sites in Good (%)	No. of sites in Fair (%)	No. of sites in Poor (%)
BOD	92 (12.8%)	452 (62.8%)	152 (21.1%)	24 (3.3%)
Benthic diatoms	152 (21.1%)	189 (26.3%)	197 (27.4%)	182 (25.3%)
Macroinvertebrates	300 (41.7%)	224 (31.1%)	129 (17.9%)	67 (9.3%)
Fish	31 (4.3%)	177 (24.6%)	331 (46.0%)	181 (25.1%)
Habitat–riparian quality	129 (17.9%)	450 (62.5%)	125 (17.4%)	16 (2.2%)

metrics was used to classify environmental condition into four classes (A: Excellent; B: Good; C: Fair; D: Poor). The range of modified IBI scores for each class was established based on those of Karr (1981) and on the scores of reference streams. Detailed information on the development and classification of numerical criteria for fish has been provided by An *et al.* (2006).

Habitat–riparian quality

The physical structure of a river provides a template for biotic interactions and associations (Thompson *et al.*, 2001). Thus, assessment of ecological condition and sound management of ecosystems depend on knowledge of the relevant biotic and abiotic settings and processes. This is particularly true for lotic ecosystems, where abiotic settings influenced by geomorphology are likely to govern and regulate biological adaptation (Brierley and Fryirs, 2005). Thus, habitat and adjacent riparian quality are important components to take into account for river restoration.

Various protocols have been developed and applied to assess physical habitat condition in countries such as the United States, Germany, England, and Japan (NRA, 1992; Otto, 1995; EEA, 1996; Barbour *et al.*, 1999; USGS, 2002). These protocols have been applied worldwide and are currently recognized as appropriate for the qualitative evaluation of habitats. In Korea, Cho (1997) first proposed a stream visual assessment protocol, the stream naturalness index (SNI). This protocol was compatible with those developed in the aforementioned countries. Cho's protocol categorized the physical structure of rivers into six groups, which were further itemized into 24 variables. Although the SNI provided detailed information on physical habitat structure, the assessment process was somewhat tedious and took considerable time to complete.

When developing NAEMP, Cho's variables were reanalyzed. Ten core matrices were selected and grouped with four properties: channel development, lateral and longitudinal connectivity, substrate condition, and riparian land use. The applicability of the modified index, named the "habitat–riparian quality index," was verified with the support of strong significant correlations between the results calculated using the habitat–riparian quality index and those obtained using the SNI in various rivers/streams. Jeong *et al.* (2008) reported detailed information on the modified index.

NAEMP assessment results

Classification of the environmental condition of Korean rivers/streams

Monitoring results using the biological and other physico-chemical criteria under NAEMP strongly suggest that the ecological integrity of streams in Korea is severely degraded. As shown in Table 3, the class distributions of the BOD, benthic diatoms, and fish criteria strongly indicate severe degradation of sampling sites. The sum of classes C (Fair) and D (Poor) is 24.4% for BOD and more than 52% for the diatom criteria. Monitoring results using macroinvertebrate criteria show slightly better ecological status of sampling sites. The results of the fish criteria indicated that more than 71% of surveyed sites were in "Fair" to "Poor" condition. The habitat quality of sampling sites was better than the biological and water chemical quality. About 80% of sampling sites were in at least "Good" condition using the habitat–riparian quality criteria.

Interestingly, the proportions of each criteria and BOD show somewhat different environmental status among the sampling sites in Table 3. For example, the distributions of BOD and macroinvertebrates are centered on class B (Good) and class C (Fair), while the monitoring results of benthic diatoms are evenly distributed across the four classes. Fish results show a skewed distribution toward classes C (Fair) and D (Poor), and the habitat quality is centered on class B (Good). These differences indicate that different biological criteria capture multiple aspects of the environmental status of stream waters. These results suggest that precise ecological integrity of a stream cannot be assessed using a single index due to the complexity of the lotic environment and the diverse responses of aquatic communities (*e.g.*, Brierley and Fryirs, 2005).

Relationships among NAEMP criteria and their implications

The relationships among biological criteria and between biological and chemical indicators including BOD, TN, and TP under NAEMP were examined by correlation analysis, as shown in Table 4. Nutrients, including TN and TP, were significantly related with all biological criteria. In particular, the macroinvertebrate class showed the strongest relationships with TN ($r = 0.42$) and TP ($r = 0.39$). BOD was also closely associated with all

Table 4. Spearman rank correlation coefficients among NAEMP criteria and chemical parameters among 720 sites (2009).

		Biological and habitat classes[a]			
		Diatom	Macroinvertebrate	Fish	Habitat quality
Chemical parameters	TN (mg.L^{-1})	0.34*	0.42*	0.36*	0.25*
	TP (mg.L^{-1})	0.25*	0.39*	0.34*	0.22*
	BOD (mg.L^{-1})	0.38*	0.50*	0.43*	0.29*
Biological classes[a]	Diatom	–	0.45*	0.39*	0.27*
	Macroinvertebrate	0.45*	–	0.52*	0.41*
	Fish	0.39*	0.52*	–	0.32*

*$p < 0.01$.
[a]The classes of biological indicators were re-coded for correlation analysis as "Class A (Excellent)" = 1, "Class B (Good)" = 2, "Class C (Fair)" = 3, and "Class D (Poor)" = 4.

biological criteria. BOD showed very close relationships with macroinvertebrates ($r = 0.50$) and fish ($r = 0.43$). Thus, water chemistry, including the nutrients in water, seems to be a basic factor for understanding the ecological status of communities in Korean streams.

The correlations of TN, TP, and BOD classes with biological criteria, shown in Table 4, suggest that overall macroinvertebrate criteria might be more sensitive to changes in water chemistry. However, the results of simple correlation analysis and the comparison of correlation coefficients cannot conclusively determine which indicator is more sensitive to water quality degradation. Different strengths of relationships between biological criteria and water chemistry may suggest different responses among various aquatic communities to stream conditions, which vary both temporally and spatially (Flinders *et al.*, 2008). Macroinvertebrates seem to have close associations with different kinds of natural and anthropogenic stresses (Pearson and Rosenberg, 1978; Weisberg *et al.*, 1997). For example, different mayfly taxa show variation in their ranges of tolerance to nutrient levels (Beketov, 2004). Thus the pollution tolerance of each taxon has been a key concept in developing indicators for the evaluation of diverse anthropogenic influences on stream ecosystems (Word, 1978, 1980, 1990; Smith *et al.*, 2001, 2007).

Benthic diatoms also respond to substrate type, the flow velocity of water, the presence of riffles, and water chemistry, particularly nutrients, in various ways. For example, van Dam *et al.* (1994) reported that nitrogen-heterotrophic diatoms require organic nitrogen for their metabolism and that the abundance of benthic diatoms can increase with increasing stream nutrients. Conversely, Patrick (1977) suggested that diatom abundance often decreases in response to increasing toxin and nutrient concentrations in water. Nutrient enrichment produces excessive algal growth, which in turn adversely affects stream animal communities (Nordin, 1985). The most common ecological phenomena caused by nutrient enrichment are increases in periphyton biomass (Bourassa and Cattaneo, 1998), shifts in macroinvertebrate communities from sensitive to more tolerant species (Allan, 2004; Chambers *et al.*, 2006), and biodiversity losses (Nijboer and Verdonschot, 2004).

Fishes are also vulnerable to eutrophication and water chemistry changes, both directly and indirectly through changes in the biological conditions of benthic diatoms and macroinvertebrates in the food chain. In fact, the fish class is closely correlated with the macroinvertebrate class ($r = 0.52$) in Table 4. As a measure of population abundance, the total number of individuals in the IBI generally reflects in-stream habitat quality, the presence of toxic substances (Karr *et al.*, 1986), and the availability of appropriate resources and water chemistry (Angermier and Karr, 1986; Berkman and Rabeni, 1987). Significant relationships among biological criteria, particularly fish and macroinvertebrates, have been reported from various geographic regions (Paller, 2001; Bryce and Hughes, 2003; Griffith *et al.*, 2005), supporting our findings of strongest correlations between macroinvertebrates and fish ($r = 0.52$), followed by diatoms and macroinvertebrates ($r = 0.45$) and diatoms and fish ($r = 0.39$) (Table 4).

The habitat–riparian quality criteria reflect human disturbances including land uses near streams and the presence of artificial stream structures including weirs and dams, as well as the cross-sectional stream structure and habitat quality. Given the relatively lower correlation coefficient values compared with those among biological criteria, the class of habitat–riparian quality was significantly correlated with biological criteria and water chemistry parameters. Specifically, the class of habitat–riparian quality was significantly related with benthic diatoms ($r = 0.27$), macroinvertebrates ($r = 0.41$), and fish ($r = 0.32$), suggesting that the physical structure of streams and riparian areas, and land uses in watersheds, also affect in-stream biological communities and water quality. Lammert and Allan (1999) reported that 50% of the variation in biotic integrity scores of headwater fish communities across seven sub-watersheds was explained by land use in the watersheds, and Roth *et al.* (1996) found that habitat integrity was closely tied to local land uses. It has been widely demonstrated that macroinvertebrate communities are more likely to respond to local- and regional-scale conditions than to catchment land use (Richards *et al.*, 1997; Lammert and Allan, 1999; Sponseller *et al.*, 2001), although watershed-scale land use has been shown to be an important predictor of macroinvertebrate communities in other studies (Li *et al.*, 2001; Townsend *et al.*, 2003; Kratzer *et al.*, 2006). Notably, water chemistry is also generally a more significant variable in explaining the community variance of fish and macroinvertebrates than

are habitat quality and land use intensity (Sawyer *et al.*, 2003; Hering *et al.*, 2006). The macroinvertebrate and fish classes showed a closer relationship with BOD ($r = 0.50$, 0.43, respectively) than with habitat quality ($r = 0.41$, 0.32, respectively), confirming the findings of previous studies.

Nonetheless, numerous studies have reported that watershed land use influences the physical and chemical characteristics of streams, including water and habitat quality (Omernik *et al.*, 1981; Osborne and Wiley, 1988; Richards *et al.*, 1993; Allan, 1995; Richards *et al.*, 1996; Allan *et al.*, 1997), and the ecological communities in streams (Roth *et al.*, 1996; Allan *et al.*, 1997; Kennen, 1999; Wang *et al.*, 2001; Roy *et al.*, 2003; Moerke and Lamberti, 2006). Companion studies under NAEMP at site and regional scales have indicated significant relationships between human land uses, including urban and agricultural land uses, and all biological criteria for streams in Korea; human uses have been found to negatively affect biological criteria, while natural areas have shown positive effects on biological communities in streams (Wallace *et al.*, 1997; Moore and Palmer, 2005). Land use seems particularly critical to biological communities when impervious cover within a watershed reaches 8–20% (Schuler, 1994; Karr and Chu, 2000), and becomes irreparably damaging in the range of 25–60% (Karr and Chu, 2000).

Implementation and conclusions

Under NAEMP, biological and habitat–riparian criteria have been developed for assessing the ecological status of rivers and streams in Korea, and their ecological integrity has been monitored since 2007. The MOE and the National Institute of Environmental Research (NIER), Korea, have published the monitoring results annually as written reports and GIS maps. The monitoring results play an important role in government-led river/stream management strategies and have motivated a sharp increase in activities to restore aquatic ecosystems nationwide. In conjunction with this paradigm shift in water environment management, budgets for stream management, restoration, and environmental education programs have continuously increased. The MOE recommends that all local governments establish region-specific biological goals for the rivers/streams within their administrative watershed boundaries and prepare detailed roadmaps, including management and restoration plans, to achieve their goals in accordance with the monitoring results. The monitoring results and annual reports have also stimulated research interest and have encouraged studies on rivers/streams and their ecological status. Previous studies on ecological status typically focused on small parts of stream networks, using only a few criteria because of insufficient budgets for long-term and wide-ranging investigation. However, the monitoring reports provide scientists, researchers, and policy makers with a nationwide picture and database of the ecological status of stream networks, including various criteria such as water chemistry and multi-biological criteria. Furthermore, the GIS database

can be used for direct comparison with local assessment results and management plans.

Despite the overall success of the initial stages of NAEMP, some issues must still be addressed. One of the most significant issues is how to deal with discrepancies among investigators in terms of sampling methods and ability to identify biotic assemblages. Over 40 researchers are participating in the investigation. Since the beginning of the program, quality control and assurance have been focal aspects, particularly in field sampling and analysis, biological identification, and digital database recording. The basic protocol for the surveys and analyses was established in 2007, and all investigators use the same protocol. Moreover, the protocol has been corrected and improved every year through an annual workshop and two interim meetings including investigators participating in the program and outside experts. We expect that discrepancies will be minimized as surveyors become more trained and experienced.

The second issue is the time frame required for field sampling to occur simultaneously nationwide. The monitoring was designed to be conducted twice a year during spring and fall. The key idea behind this monitoring frequency was to perform the field surveys before and after the heavily concentrated precipitation in summer (Asian monsoon). However, it is becoming difficult to conduct field samplings within the designed time frames due to irregular concentrated precipitation patterns in spring and fall (KMA, 2008). In addition, concentrated precipitation causes potential flooding, which may lead to *post hoc* construction and stream bank enhancement projects, often conducted during the survey periods. The effects of such projects could cause imprecise assessments. Thus, in the future, the time frame for field sampling might need to be adjusted from year to year, considering yearly weather patterns and construction.

The third issue relates to data analysis. As discussed earlier, NAEMP results confirm previous findings that indicate a strong tie between anthropogenic disturbances around rivers/streams and changes in water chemistry with biological criteria on various spatial scales (*e.g.*, Schuler, 1994; Wallace *et al.*, 1997; Karr and Chu, 2000; Moore and Palmer, 2005). However, these studies show only a large picture of the impacts of human disturbance (*i.e.*, stress) on lotic environments and their resident biological assemblages but cannot explain assemblage-specific responses to stress. Relatively few studies have examined the responses of different assemblages to stress (Paller, 2001; Bryce and Hughes, 2003; Sawyer *et al.*, 2003; Griffith *et al.*, 2005; Hering *et al.*, 2006). Such understanding is critical in watershed management and stream/river restoration for targeting particular assemblages in specific streams/rivers and for building ecological models. In addition, it is necessary to examine whether the relationships between various stress types and assemblage-specific responses are linear or threshold responsive. Some studies have reported that these relationships are curvilinear or stepwise functions (Davis and Simon, 1995; Wang *et al.*, 2001), while other studies have suggested a linear form (Booth, 2005;

Cuffney *et al.*, 2005; Kennen *et al.*, 2005; Morgan and Cushman, 2005; Roy *et al.*, 2005; Waite *et al.*, 2008).

Although a few issues remain to be settled, NAEMP is a promising program. The monitoring results have already had considerable impacts on policy making and scientific research relevant to lotic environments and watershed management in Korea. In the future, NAEMP results will be incorporated into more aggressive regulations for the preservation and restoration of relevant streams/rivers, buffer areas, and watersheds. Future research will also focus on the development of aquatic ecological modeling based on the monitoring results. Accumulating more data and conducting further research are also important in better understanding the complex structure of lotic ecosystems and their functions and explaining interactive relationships among biotic assemblages and their complex responses to anthropogenic disturbances.

References

Allan J.D., 1995. Stream ecology: structure and function of running waters, Chapman and Hall, London.

Allan J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annu. Rev. Ecol. Evol. Syst.*, *35*, 257–284.

Allan J.D., Erickson D.L. and Fay J., 1997. The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biol.*, *37*, 149–161.

An K.-G., Jung S.H. and Choi S.S., 2001. An evaluation on health conditions of Pyongchang River using the index of biological integrity (IBI) and qualitative habitat evaluation index (QHEI). *Korean J. Limnol.*, *34*, 153–165 (in Korean).

An K.-G., Lee J.Y., Bae D.-Y., Kim J.-H., Hwang S.-J., Won D.-H., Lee J.-K. and Kim C.-S., 2006. Ecological assessments of aquatic environment using multi-metric model in major nationwide stream watershed. *J. Korean Sco. Water Qual.*, *22*, 796–804 (in Korean).

Angermier P.L. and Karr J.R., 1986. Applying an index of biotic integrity based on stream fish communities: considerations in sampling and interpretation. *N. Am. J. Fish. Manage.*, *6*, 418–429.

Barbour M.T., Gerritsen J., Snyder B.D. and Stribling J.B., 1999. Rapid Bioassessment Protocols for Use in Streams and Rivers: Periphyton, Benthic Macroinvertebrates, and Fish, 2nd edn., EPA 841/B-99/002, US Environmental Protection Agency, Washington, DC.

Beketov M.A., 2004. Different sensitivity of mayflies (Insecta, Ephemeroptera) to ammonia, nitrite and nitrate: linkage between experimental and observational data. *Hydrobiologia*, *528*, 209–216.

Berkman H.E. and Rabeni C.F., 1987. Effect of siltation on stream fish communities. *Environ. Biol. Fish.*, *18*, 285–294.

Bolstad P.V. and Swank W.T., 1997. Cumulative impacts of land use on water quality in a southern Appalachian watershed. *J. Am. Water Res. Assoc.*, *33*, 519–533.

Booth D.B., 2005. Challenges and prospects for restoring urban streams: a perspective from the Pacific Northwest of North America. *J. N. Am. Benthol. Soc.*, *24*, 724–737.

Bourassa N. and Cattaneo A., 1998. Control of periphyton biomass in Laurentian streams. *J. N. Am. Benthol. Soc.*, *17*, 420–429.

Brierley G.J. and Fryirs K.A., 2005. Geomorphology and River Management-Application of the River Style Framework, Blackwell Publishing, Oxford, 398 p.

Bryce S.A. and Hughes R.M., 2003. Variable assemblage responses to multiple disturbance gradients: case studies in Oregon and Appalachia, USA. *In*: Simon T.P. (ed.), Biological Response Signatures: Indicator Patterns Using Aquatic Communities, CRC Press, Boca Raton, FL, 539–560.

Carlisle D.M., Falcone J. and Meador M.R., 2009. Predicting the biological condition of streams: use of geospatial indicators of natural and anthropogenic characteristics of watersheds. *Environ. Monit. Assess.*, *151*, 143–160.

Chambers P.A., Meissner R., Wrona F.J., Rupp H., Guhr H., Seeger J., Culp J.M. and Brua R.B., 2006. Changes in nutrient loading in an agricultural watershed and its effects on water quality and stream biota. *Hydrobiologia*, *556*, 399–415.

Chandler J.R., 1970. A biological approach to water quality management. *Water Pollut. Control*, *69*, 415–422.

Cho Y.H., 1997. A study on evaluation method of stream naturalness for ecological restoration of stream corridors. *J. Korean Inst. Landscape Arch.*, *25*, 2073–2081 (in Korean).

Chung J., 1987. An assessment of water quality by epilithic diatoms of Hyungsan River water-system. *Korean J. Phycol.*, *2*, 139–146 (in Korean).

Chung Y.H., Shin J.H. and Lee M.J., 1965. A study on the microflora of the Han River. I. The phytoplankton and the effect of the marine water in the lower course of the Han River. *Korean J. Bot.*, *8*, 7–29 (in Korean).

Cuffney T.F., Zappia H., Giddings E.M.P. and Coles J.F., 2005. Effects of urbanization on benthic macroinvertebrate assemblages in contrasting environmental settings: Boston, Birmingham, and Salt Lake City. *In*: Brown L.R., Gray R.H., Hughes R.M. and Meador M.R. (eds.), Effects of Urbanization on Stream Ecosystems, Am. Fish. Soc., Symp., 47, Bethesda, Maryland, 361–408.

Davies S.P. and Jackson S.K., 2006. The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. *Ecol. Appl.*, *16*, 1251–1266.

Davis W.S. and Simon T.P. (eds.), 1995. Biological Assessment and Criteria. Tools for Resource Planning and Decision Making, Lewis Publishers, Boca Raton, FL, 415 p.

Deshon J.E., 1995. Development and application of the invertebrate community index (ICI). *In*: Davis W.S. and Simon T.P. (eds.), Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making, Lewis Publishers, Boca Raton, FL, 217–243.

DIN 38410, 1990. Biological-ecological analysis of water (group M): determination of the saprobic index (M2). German standard methods for the examination for water, Part 2, Wastewater and sludge, 10 p.

EEA, 1996. EEA Report. Surface water quality monitoring: 4.2. Biological assessments, Topic Report No. 2, http://reports.eea.eu.int/92-9167-001-4/page021.html.

Flinders C.A., Horwitz R.J. and Belton T., 2008. Relationship of fish and macroinvertebrate communities in the mid-Atlantic

uplands: implications for integrated assessments. *Ecol. Indic.*, 8, 588–598.

Gammon J.R., 1976. The fish populations of the middle 340 km of the Wabash River, Purdue University Water Resources Research Center Technical Report 86, Lafayette, IN.

Gburek W.J. and Folmar G.J., 1999. Flow and chemical contributions to streamflow in an upland watershed: a baseflow survey. *J. Hydrologia*, 217, 1–18.

Griffith M.B., Hill B., Mccormick H., Kaufmann R., Herlihy T. and Selle A.R., 2005. Comparative application of indices of biotic integrity based on periphyton, macroinvertebrates, and fish to southern Rocky Mountain streams. *Ecol. Indic.*, 5, 117–36.

Hering D., Johnson R.K., Kramm S., Schmutz S., Szoszkiewicz K. and Verdonschot P.F.M., 2006. Assessment of European streams with diatoms, macrophytes, macroinvertebrates, and fish: a comparative metric-based analysis of organism response to stress. *Freshwater Biol.*, 51, 1757–1785.

Hilsenhoff W.L., 1977. Use of arthropods to evaluate water quality of streams, Technical Bulletin of the Wisconsin Department of Natural Resources, 100, Madison, WI, 15 p.

Hilsenhoff W.L., 1982. Using a biotic index to evaluate water quality of streams, Technical Bulletin of the Wisconsin Department of Natural Resources, 132, Madison, WI.

Hwang S.-J., Kim N.-Y., Won D.H., An K.G., Lee J.K. and Kim C.S., 2006. Biological assessment of water quality by using epilithic diatoms in major river systems (Geum, Youngsan, Seomjin River), Korea. *J. Korean Sco. Water Qual.*, 22, 784–795 (in Korean).

Jeong K.-S., Joo G.-J., Kim D.K., Lineman M., Kim S.-H., Jang I., Hwang S.-J., Kim J.-H., Lee J.-K. and Byeon M.S., 2008. Development of habitat–riparian quality indexing system as a tool of stream health assessment: case study in the Nakdong River basin. *Korean J. Limnol.*, 41, 499–511 (in Korean).

Johnson R.K., Furse M.T., Hering D. and Sandin L., 2007. Ecological relationships between stream communities and spatial scale: implications for designing catchment-level monitoring programmes. *Freshwater Biol.*, 52, 939–958.

Karr J.R., 1981. Assessment of biological integrity using fish communities. *Fisheries*, 6, 21–27.

Karr J.R. and Chu E.W., 1999. Restoring Life in Running Waters: Better Biological Monitoring, Island Press, Washington, DC.

Karr J.R. and Chu E.W., 2000. Sustaining living rivers. *Hydrobiologia*, 422/423, 1–14.

Karr J.R., Fausch K.D., Angermeier P.L., Yant P.R. and Schlosser I.J., 1986. Assessing biological integrity in running waters: a method and its rationale, Special Publication 5, Illinois Natural History Survey, Champaign, IL.

Kelly M.G. and Whitton B.A., 1995. The trophic diatom index: a new index for monitoring eutrophication in rivers. *J. Appl. Phycol.*, 7, 433–444.

Kelly M.G., Bennion H., Burgess A., Ellis J., Juggins S., Guthrie R., Jamieson J., Adriaenssens V. and Yallop M., 2009. Uncertainty in ecological status assessments of lakes and rivers using diatoms. *Hydrobiologia*, 633, 5–15.

Kennen J.G., 1999. Relation of macroinvertebrate community impairment to catchment characteristics in New Jersey streams. *J. Am. Water Res. Assoc.*, 35, 939–955.

Kennen J.G., Chang M. and Tracy B.H., 2005. Effects of landscape change on fish assemblage. *In*: Brown L.R.,

Gray R.H., Hughes R.M. and Meador M.R. (eds.), Effects of Urbanization on Stream Ecosystems, Am. Fish. Soc., Symp., 47, Bethesda, Maryland, 39–52.

KMA (Korea Meteorological Administration), 2008. Climate change status and response plan, 2 p. (in Korean).

Kong D.S., Ryu H.I., Ryu J.K. and Yoon I.B., 1995. The development and application of higher taxa biotic index (HTBI) by benthic macroinvertebrates. *P. Korean J. Environ. Toxicol.*, 11 (in Korean).

Kratzer E.B., Jackson J.K., Arscott D.B., Aufdenkampe A.K., Dow C.L., Kaplan L.A., Newbold J.D. and Sweeney B.W., 2006. Macroinvertebrate distribution in relation to land use and water chemistry in New York City drinking-water-supply watersheds. *J. N. Am. Benthol. Soc.*, 25, 954–976.

Kutka F.J. and Richards C., 1996. Relating diatom assemblage structure to stream habitat quality. *J. N. Am. Benthol. Soc.*, 15, 469–480.

Kwon Y.S. and An K.-G., 2006. Biological stream health and physico-chemical characteristics in the Keumho River watershed. *Korean J. Limnol.*, 39, 145–156 (in Korean).

Lammert M. and Allan J.D., 1999. Assessing biotic integrity of streams: effects of scale in measuring the influence of land use/cover and habitat structure on fish and macroinvertebrates. *Environ. Manage.*, 23, 257–270.

Lee H.D., 1977. A study of Saprobien system according to the water pollution in Han River. *Korean J. Limnol.*, 10, 47–52 (in Korean).

Lee S.W., Hwang S.J., Lee S.B., Hwang H.S. and Sung H.C., 2009. Landscape ecological approach to the relationships of land use patterns in watersheds to water quality characteristics. *Landscape Urban Plan.*, 92, 80–89.

Lenat D.R. and Crawford J.K., 1994. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. *Hydrobiologia*, 294, 185–199.

Levin S.A., 1992. The problem of pattern and scale in ecology. *Ecology*, 73, 1943–1967.

Li J., Herlihy A., Gerth W., Kaufmann P., Gregory S., Urquhart S. and Larsen D.P., 2001. Variability in stream macroinvertebrates at multiple spatial scales. *Freshwater Biol.*, 46, 87–97.

Liu A.J., Tong S.T.Y. and Goodrich J.A., 2000. Land use as a mitigation strategy for the water-quality impacts of global warming: a scenario analysis on two watersheds in the Ohio River Basin. *Environ. Eng. Policy*, 2, 65–76.

McCarron E. and Frydenborg R., 1997. The Florida bioassessment program: an agent for change. *Hum. Ecol. Risk Assess.*, 3, 967–977.

MOE/NIER, 2006. Study on development of methods for synthetic assessment of water environment, The Ministry of Environment/National Institute of Environmental Research, Korea (in Korean).

MOE/NIER, 2007. Establishment of monitoring network for survey and evaluation of aquatic ecosystem health, The Ministry of Environment/National Institute of Environmental Research, Korea (in Korean).

MOE/NIER, 2008. Survey and evaluation of aquatic ecosystem health in Korea, The Ministry of Environment/National Institute of Environmental Research, Korea (in Korean).

Moerke A.H. and Lamberti G.A., 2006. Scale-dependent influences on water quality, habitat, and fish communities in the streams of the Kalamazoo River Basin, Michigan (USA). *Aquat. Sci.*, 68, 193–205.

Moore A.A. and Palmer M.A., 2005. Invertebrate biodiversity in agricultural and urban headwater streams: implications for conservation and management. *Ecol. Appl.*, *15*, 1169–1177.

Morgan R.P. and Cushman S.F., 2005. Urbanization effects on stream fish assemblages in Maryland, USA. *J. N. Am. Benthol. Soc.*, *24*, 643–655.

National River Authority (NRA), 1992. River Corridor Surveys, NRA, Bristol.

Nerbonne B.A. and Vondracek B., 2001. Effects of local land use on physical habitat, benthic macroinvertebrates, and fish in the Whitewater River, Minnesota, USA. *Environ. Manage.*, *28*, 87–99.

Nielsen L.A. and Johnson D.L., 1983. Fisheries Techniques, American Fisheries Society, Bethesda, MD.

NIER, 2003. Comprehensive plan of survey and research on development of methods for synthetic assessment of water quality, The National Institute of Environmental Research, Korea (in Korean).

Nijboer R.C. and Verdonschot P.F.M., 2004. Variable selection for modelling effects of eutrophication on stream and river ecosystems. *Ecol. Model.*, *177*, 17–39.

Nõges P., van de Bund W., Cardoso A.C., Solimini A. and Heiskanen A.-S., 2009. Assessments of the ecological status of European surface waters: a work in progress. *Hydrobiologia*, *633*, 197–211.

Nordin R.N., 1985. Water Quality Criteria for Nutrients and Algae (Technical Appendix), http://www.elp.gov.bc.ca/wat/wq/BCguidelines/nutrients.html.

Ode P.R., Hawkins C.P. and Mazor R.D., 2008. Comparability of biological assessments derived from predictive models and multimetric indices of increasing geographic scope. *J. N. Am. Benthol. Soc.*, *27*, 967–985.

Oh Y.N. and Chon T.S., 1991. A study on the benthic macroinvertebrates in the middle reaches of the Paenae stream, a tributary of the Naktong River, Korea. *Korean J. Ecol.*, *14*, 345–360 (in Korean).

Omernik J.M., Abernathy A.R. and Male L.M., 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. *J. Soil Water*, *36*, 227–231.

Osborne L.L. and Wiley M.J., 1988. Empirical relationships between land use/cover and stream water quality in an agricultural watershed. *J. Environ. Manage.*, *26*, 9–27.

Osborne P.E. and Suárez-Seoane S., 2002. Should data be partitioned spatially before building large-scale distribution models? *Ecol. Model.*, *157*, 249–259.

Otto A., 1995. Gewässerstrukturgütekartierung in der Bundesrepublik Deutschland, Teil 1, Verfahrensentwurf für kleine und mittelgroße Fließ gewässer der freien Landschaft im Bereich der Mittelgebrige, des Hügellandes und des Flachlandes, Lanesamt für Wasserwirtschaft Rheinland-Pfalz.

Paller M.H., 2001. Comparison of fish and macroinvertebrate bioassessments from South Carolina coastal plain streams. *Aquat. Ecosyst. Health Manage.*, *4*, 175–186.

Passy S.I., Rode R.W., Carlson D.M. and Novak M.A., 2004. Comparative environmental assessment in the studies of benthic diatom, macroinvertebrate, and fish communities. *Int. Rev. Hydrobiol.*, *89*, 121–138.

Patrick R., 1977. Effects of trace metals in the aquatic ecosystem. *Am. Sci.*, *66*, 185–191.

Pearson T. and Rosenberg R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Annu. Rev. Oceanogr. Mar. Biol.*, *16*, 229–311.

Pont D., Hugueny B., Beier U., Goffaux D., Melcher A., Noble R., Rogers C., Roset N. and Schmutz S., 2006. Assessing river biotic condition at a continental scale: a European approach using functional metrics and fish assemblages. *J. Appl. Ecol.*, *43*, 70–80.

Prygiel J., Whitton B.A. and Bukowska L. (eds.), 1999. Use of algae for monitoring rivers III. *In*: Proceedings of an International Symposium, Agence de l'Eau Artois-Picardie, Douai Cedex, France, 271 p.

Richards C., Host G.E. and Arthur J.W., 1993. Identification of predominant environmental factors structuring stream macroinvertebrate communities within a large agricultural catchment. *Freshwater Biol.*, *29*, 285–294.

Richards C., Johnson L.B. and Host G.E., 1996. Landscape scale influences on stream habitats and biota. *Can. J. Fish Aquat. Sci.*, *53* (Suppl. I), 295–311.

Richards C., Haro R.J., Johnson L.B. and Host G.E., 1997. Catchment and reach-scale properties as indicators of macroinvertebrate species traits. *Freshwater Biol.*, *s37*, 219–230.

Roth N.E., Allan J.D. and Erickson D.L., 1996. Landscape influences on stream biotic integrity assessed at multiple spatial scales. *Landscape Ecol.*, *11*, 141–156.

Roy A.H., Rosemond A.D., Paul M.J., Leigh D.S. and Wallace J.B., 2003. Stream macroinvertebrate response to catchment urbanisation (Georgia, U.S.A.). *Freshwater Biol.*, *48*, 329–346.

Roy A.H., Freeman M.C., Freeman B.J., Wenger S.J., Ensign W.E. and Meyer J.L., 2005. Investigating hydrologic alteration as a mechanism of fish assemblage shifts in urbanizing streams. *J. N. Am. Benthol. Soc.*, *24*, 656–678.

Sawyer J.A., Stewart P.M., Mullen M.M., Simon T.P. and Bennett H.H., 2003. Influence of habitat, water quality, and land use on macro-invertebrate and fish assemblages of a southeastern coastal plain watershed, USA. *Aquat. Ecosyst. Health Manag.*, *7*, 85–99.

Schuler T.R., 1994. The importance of imperviousness. *Watershed Protect. Tech.*, *1*, 100–111.

Simon T.P. (ed.), 1999. Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities, CRC Press, Boca Raton, FL, 652 p.

Simon T.P., 2000. The use of biological criteria as a tool for water resource management. *Environ. Sci. Policy*, *3*, S43–S49.

Skvortzow B.W., 1929. Fresh-water diatoms from Korea, Japan. *Phillipines J. Sci.*, *38*, 283–291.

Smith A.J., Bode R.W. and Kleppel G.S., 2007. A nutrient biotic index (NBI) for use with benthic macroinvertebrate communities. *Ecol. Indic.*, *7*, 371–386.

Smith R.W., Bergen M., Weisberg S.B., Cadien D., Dankey A., Montagne D., Stull J.K. and Velarde R.G., 2001. Benthic response index for assessing infaunal communities on the mainland shelf of Southern California. *Ecol. Appl.*, *11*, 1073–1087.

Sponseller R.A., Benfield E.F. and Valett H.M., 2001. Relationships between land use, spatial scale and stream macroinvertebrate communities. *Freshwater Biol.*, *46*, 1409–1424.

Šrámek-Hušek R., 1956. Zur biologischen charakteristik der höheren saprobitätsstufen. *Arch. Hydrobiol.*, *51*, 376–390.

Stewart P.M., Scribiallo R. and Simon T.P., 1999. The use of aquatic macrophytes in monitoring and in assessment of biological integrity. *In*: Gerhardt A. (ed.), Biomonitoring of Polluted Waters – Reviews on Actual Topics, Environmental Science Forum, 96, Trans Tech Publications, Ltd., Uetikon-Zuerich, Switzerland, 275–302.

Stoddard J.L., Herlihy A.T., Peck D.V., Hughes R.M., Whittier T.R. and Tarquinio E., 2008. A process for creating multimetric indices for large-scale aquatic surveys. *J. N. Am. Benthol. Soc.*, 27, 878–891.

Swink W.R. and Wilhelm G., 1994. Plants of the Chicago region, 4th edn., Indiana Academy of Science, Indianapolis, IN.

Thompson J., Taylor M.P., Fryirs K.A. and Brierley G.J., 2001. A geomorphological framework for river characterization and habitat assessment. *Mar. Freshwater Ecosyst.*, 11, 373–389.

Tong S.T.Y. and Chen W., 2002. Modeling the relationship between land use and surface water quality. *J. Environ. Manage.*, 66, 377–393.

Townsend C.R., Dolédec S., Norris R., Peacock K. and Arbuckle C., 2003. The influence of scale and geography on relationships between stream community composition and landscape variables: description and prediction. *Freshwater Biol.*, 48, 768–785.

Tsuda M., 1964. Biology of Polluted Waters, Hokuryu-kan, Tokyo.

UNESCO, 2004. Integrated watershed management – Ecohydrology and phytotechnology – Manual, UNESCO Regional Bureau for Science in Europe, Venice, Italy.

U.S. Environmental Protection Agency (EPA), 1990. Biological Criteria: National Program Guidance for Surface Waters, US EPA, Office of Water Regulations and Standards, Washington, DC, EP-440/5-90-004, April.

U.S. Environmental Protection Agency (EPA), 2002. Biological assessments and criteria: crucial components of water quality programs, EPA 822-F-02-006, Washington, DC.

U.S. Geological Survey (USGS), 2002. Revised protocols for sampling algal, invertebrate, and fish communities as part of the national water-quality assessment program, Open-file Report 02-150, Virginia.

van Dam H., Mertens A. and Sinkeldam J., 1994. A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. *Netherlands J. Aquat. Ecol.*, 28, 117–133.

Waite I.R., Brown L.R., Kennen J.G., May J.T., Cuffney T.F., Orlando J.L. and Jones K.A., 2008. Comparison of watershed disturbance predictive models for stream benthic macroinvertebrates for three distinct ecoregions in western US. *Ecol. Indic.*, 10, 1125–1136.

Wallace J.B., Eggert S.L., Meyer J.L. and Webster J.R., 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. *Science*, 277, 102–104.

Wang L., Lyons J., Kanehl P. and Bannerman R., 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environ. Manage.*, 28, 255–266.

Washington H.G., 1984. Diversity, biotic and similarity indices: a review with special relevance to aquatic ecosystems. *Water Res.*, 18, 653–694.

Watanabe T., Asai K. and Houki A., 1990. Numerical simulation of organic pollution in flowing waters. *Enc. Env. Control Tech.*, 4, 251–281.

Weisberg S.B., Ranasinghe J.A., Dauer D.M., Schaffner L.C., Diaz R.J. and Frithsen J.B., 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. *Estuaries*, 20, 149–158.

Won D.H., Jun Y.-C., Kwon S.-J., Hwang S.-J., Ahn K.-G. and Lee J.-W., 2006. Development of Korean saprobic index using benthic macroinvertebrates and its application to biological stream environment assessment. *J. Korean Sco. Water Qual.*, 22, 768–783 (in Korean).

Woodiwiss F.S., 1978. Comparative study of biological-ecological water quality assessment methods. Second practical demonstration, Nottingham (20 Sept. to 1 Oct. 1976), Summary Report, Commission of the European Communities, Environment and Consumer Protection Service.

Word J.Q., 1978. The infaunal trophic index. Coastal Water Research Project Annual Report, Southern California Coastal Water Research Project, El Segundo, CA, 19–39.

Word J.Q., 1980. Classification of benthic invertebrates into infaunal trophic index feeding groups, Biennial Report, 1979–1980, Coastal Water Research Project, Los Angeles, CA, 103–121.

Word J.Q., 1990. The infaunal trophic index, a functional approach to benthic community analyses, Ph.D. Dissertation, University of Washington, Seattle, WA.

Wui I.S., 1974. The biological estimation of water pollution levels on the benthos fauna of the Yeong-san River. *Korean J. Limnol.*, 7, 29–35 (in Korean).

Wui I.S., Ra C.H., Choi C.G. and Baik S.K., 1983. Studies on the aquatic insects of the Tamjin River. *Korean J. Limnol.*, 16, 33–52 (in Korean).

Yeom D.H., An K.-W., Hong Y.P. and Lee S.K., 2000. Assessment of an index of biological integrity (IBI) using fish assemblages in Keumho River, Korea. *Korean J. Environ. Biol.*, 18, 215–226 (in Korean).

Yoon I.B., Kong D.S. and Ryu J.K., 1992a. Studies on the biological evaluation of water quality by benthic macroinvertebrates (I) – saprobic valency and indicative value. *Korean J. Environ. Biol.*, 10, 24–39 (in Korean).

Yoon I.B., Kong D.S. and Ryu J.K., 1992b. Studies on the biological evaluation of water quality by benthic macroinvertebrates (II) – effects of environmental factors to community. *Korean J. Environ. Biol.*, 10, 40–55 (in Korean).

Yoon I.B., Kong D.S. and Ryu J.K., 1992c. Studies on the biological evaluation of water quality by benthic macroinvertebrates (III) – macroscopic simple water quality evaluation. *Korean J. Environ. Biol.*, 10, 77–84 (in Korean).

Zelinka M. and Marvan P., 1961. Zur Präzisierung der biologischen klassifikation der Reinheid fliessender Gewässer. *Arch. Hydrobiol.*, 57, 389–407.