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Distribution patterns of fish communities with respect to environmental gradients in Korean streams

Ju-Duk Yoon[1], Jeong-Hui Kim[2], Myeong-Seop Byeon[3], Hyung-Jae Yang[3], Jong-Young Park[4], Jae-Hwan Shim[5], Ho-Bok Song[6], Hyun Yang[7] and Min-Ho Jang[2]*

[1] Department of Biological Sciences, Pusan National University, Busan 609-735, Republic of Korea
[2] Department of Biology Education, Kongju National University, Gongju 314-701, Republic of Korea
[3] Water Environment Research Department, The National Institute of Environmental Research, Inchon 404-170, Republic of Korea
[4] Department of Biological Science, Chonbuk National University, Jeonju 561-756, Republic of Korea
[5] Department of Physical Therapy, Seokang University, Gwangju 500-742, Republic of Korea
[6] Department Biological Sciences, Kangwon National University, Chuncheon 200-701, Republic of Korea
[7] Institute of Biodiversity Research, Jeonju 561-211, Republic of Korea

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Abstract – Stream development can generate environmental changes that impact fish communities. In temperate streams, the distribution of fish species is associated with environmental gradients. To analyze the relevant factors, large-scale exploration is required. Thus, to evaluate the distribution patterns of fish in Korea, sampling was conducted on a national scale at 720 sites over a 6-week period in 2009. A total of 124 fish species in 27 families were identified; *Zacco platypus* and *Zacco koreanus* of the Cyprinidae were the dominant and subdominant species, respectively. Of the species found, 46 (37.1%) were endemic and 4 (3.2%) exotic; of the latter, *Micropterus salmoides* and *Lepomis macrochirus* were widely distributed. Upon canonical correspondence analysis (CCA), both altitude and biological oxygen demand (BOD) were highly correlated with CCA axes 1 and 2, respectively. This explained 62.5% of the species–environment relationship. Altitude and stream order were longitudinally related to species distribution. The numbers of both total and endemic species gradually increased as streams grew in size to the fourth–fifth-order, and decreased in sixth-order, streams. Overall, fish communities were stable throughout the entire watershed, whereas some species showed site-specific occurrence patterns due to the paleogeomorphological characteristics of Korean peninsula. However, various anthropogenic activities may negatively affect fish communities. Therefore, both short- and long-term sustainable management strategies are required to conserve native fish fauna.

Key words: Environmental factors / longitudinal distribution / stream order / altitude / sustainable management

Introduction

A stream exists in an environment characterized by a variety of physicochemical components, and diverse aquatic organisms such as fish, insects, and plants co-exist in the stream (Allan, 1995). Freshwater fish typically rank highly in the trophic system (Moyle and Cech, 2000), and fish distribution is often influenced by environmental variables and habitat characteristics (Matthews and Robison, 1988; Matthews *et al.*, 1992; Kouamélan *et al.*, 2003; Buisson *et al.*, 2007). In temperate rivers, changes in fish communities are associated with increases in habitat diversity; the relevant factors include stream order and width, altitude, and substrate composition (Belliard *et al.*, 1997; Oberdorff *et al.*, 2001; Grenouillet *et al.*, 2004).

In aquatic ecosystems, the impact of any disturbance is felt more extensively than is the case in terrestrial ecosystems (Ricciardi and Rasmussen, 1999). The freshwater ecosystem is the system that is most threatened globally (Sala *et al.*, 2000), and freshwater fish rank second only to amphibians as endangered biota (Bruton, 1995). However, large civil engineering projects that affect rivers, such as dam and weir construction, dredging, and reclamation, proceed apace. Although the importance of conservation is widely acknowledged, development almost always takes priority (Balmford *et al.*, 2002). Changes in fish communities caused by construction projects have

*Corresponding author: jangmino@kongju.ac.kr

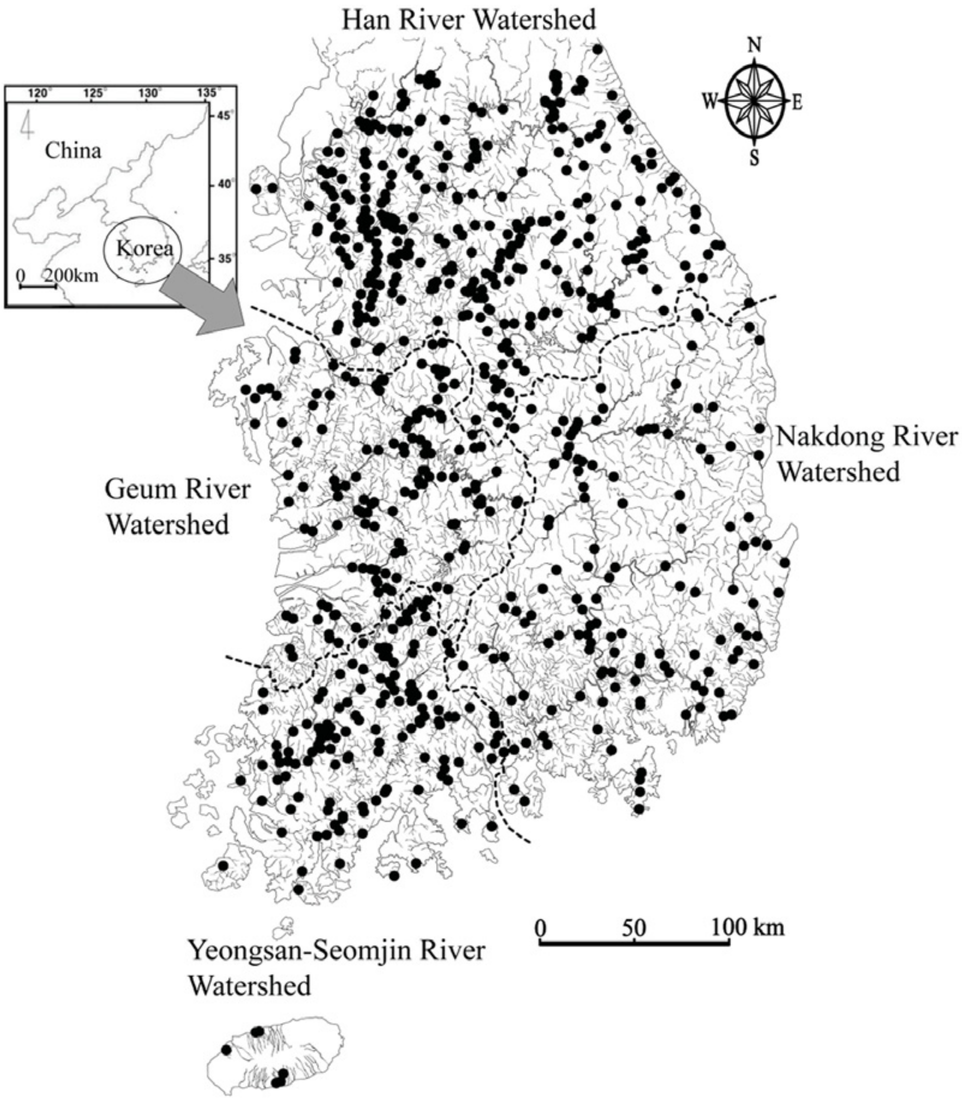

Fig. 1. A map showing the study sites. Each watershed is defined by the presence of a major river system (Han, Nakdong, Geum, and Yeongsan–Seomjin).

been widely reported (Martinez *et al*., 1994; Gehrke *et al*., 2002; Habit *et al*., 2007).

When such changes are studied, both short-term census data and long-term analysis of change are needed to adequately explore species status and distribution. Simultaneous measurement of environmental variables is also required. By these means, a large-scale research program can identify the effects of environmental variables on fish communities. Small-scale projects fail in this respect, because only a few study sites are chosen (Jackson *et al*., 2001). Although many reports on relationships between fish communities and environmental variables have appeared, and although such work is ongoing, the data cannot be easily generalized. Most previous studies were conducted on the local or watershed scale, and the overall distribution pattern of fish in Korean streams remains unclear. In the present study, we first simultaneously surveyed 720 study sites throughout the entire country, using standardized methods to evaluate the current status of fish fauna in Korea. Second, we characterized the distribution patterns of fish communities on a national scale with respect to environmental variables. Finally, we discuss strategies for conservation and management of fish in Korea.

Materials and methods

Study sites

Fish communities were surveyed at 720 study sites distributed throughout Korea (Fig. 1). The sites were located in four watersheds: the Han River Watershed (HR, 320 sites), the Nakdong River Watershed (NR, 130 sites), the Geum River Watershed (GR, 130 sites), and the Yeongsan–Seomjin River Watershed (YSR, 140 sites; this latter site has two rivers, the Seomjin and the Yeongsan). Study sites were selected based on the presence of automatic water quality monitoring stations operated by the government and a preliminary survey confirming suitability. With few exceptions, most study sites ranked higher than local second-grade streams, using the Korean stream classification system.

Fish sampling

Fish sampling was conducted over six weeks in September and October 2009, in the interval after the monsoon season but before the time at which the water temperature fell to below 19 °C. To simultaneously census all study sites, ten research teams led by highly trained fish experts were organized. All sampling and field measurements were conducted according to the guidelines of the "National Surveys for Stream Ecosystem Health in Korea" (MOE/NIER, 2008). To prevent under- or over-estimation of fish levels, fish were collected using kick nets (5 mm mesh; 1.35 m^2 [= 1.5 m × 0.9 m]) and cast nets (7 mm mesh; 4.5 m^2 [= π × 1.22 m]). Cast nets were thrown 20 times, whereas kick-net sampling was performed for 30 min at each site. The total sampling duration was 1 h. Sampling was conducted over an estimated 200 m of stream reach, ranging approximately 100 m upstream and downstream of the central point of the study site. At most sites, at least one riffle and one pool were sampled. However, this was not possible on downstream reaches of principal river channels. Although the habitat varied between upstream and downstream sampling sites, we applied the same sampling method at all sites to limit problems associated with variation in sampling equipment. All captured fish were identified, counted, and released. All specimens were identified using the criteria of Kim and Park (2002), which are based on the classification system of Nelson (1994).

Environmental variables

We measured 13 environmental variables; these were biological oxygen demand (BOD), dissolved oxygen (DO) level, pH, water depth, stream order, stream altitude, stream width, water temperature, conductivity, turbidity, total nitrogen (TN) level, concentration of NO_3-N, and the level of Chlorophyll *a* (Chl.*a*). DO level, water temperature, conductivity, and pH were measured in the field using YSI 85 meters (YSI Inc., Yellow Springs, OH, USA) and Orion 3-Star-Plus pH meters (Thermo Fisher Scientific Inc., Waltham, MA, USA). Stream width was measured employing Yardage–Prolaser rangefinders (Bushnell Co., Overland Park, KS, USA). Other variables were analyzed in the laboratory using the techniques of Eaton *et al*. (2005). Stream order was determined by Strahler's (1957) method. When no flow was evident at second-order streams, we designated such streams as first order, thus distinguishing them from streams in which flow was in fact discernible. Altitude was determined using digital elevation data (Openmate Inc., Seoul, South Korea); streams were classified into seven altitudinal groups, at 50 m intervals.

Data analysis

Canonical correspondence analysis (CCA) was conducted using CANOCO software (version 4.5; Ter Braak and Šmilauer, 2002) to evaluate relationships between fish communities and environmental variables. Thirteen environmental variables and the most common fish species (those that occurred at > 5% of the 720 study sites) were evaluated. Rare fish species were excluded from analysis; such species typically influence the results of multivariate analysis in only a minor fashion and are often perceived as outliers in ordinations (Gauch, 1982). A Monte Carlo test with 1000 permutations was used to evaluate the significance of the general model created.

Results

Fish fauna

A total of 124 species in 27 families were identified. The family Cyprinidae was the most abundant taxon, with 54 species (85.7% of total abundance), followed by the families Cobitidae and Gobiidae with 15 and 12 species, respectively. Species number was highest in the HR (91 species in 21 families) and lowest in the NR (66 species in 17 families) (Table 1). This may be due to the large number of HR study sites. Only 1–4 species of other families were identified in the various watersheds studied.

Zacco platypus (Temminck and Schlegel) and *Z. koreanus* (Kim, Oh and Hosoya) were the dominant and subdominant species, respectively, constituting 30.6 and 11.6% of total abundance. Although the exotic species *Carassius auratus* (Linnaeus) (3.0% of total abundance and found at 270 sites), *Rhinogobius brunneus* (Temminck and Schlegel) (2.9% and 218 sites), and *M. salmoides* (1.4% and 189 sites) were relatively lower in abundance, occurrence frequencies were higher.

A total of 46 endemic species (37.1% of the total number of identified species) were found; the level of endemism in each watershed was over 30% (HR 34.1%, NR 34.8%, GR 32.9%, and YSR 31.9%). Four exotic species, *Carassius cuvieri* (Temminck and Schlegel), *Oreochromis niloticus* (Linnaeus), *M. salmoides*, and *L. macrochirus* were identified; all were found in the HR and the GR. However, *O. niloticus* was not collected in the NR or the YSR (Table 1).

Species distribution patterns

Among the 124 species identified, 38 species were collected at > 5% of study sites used in CCA modeling. This modeling revealed the relationships between species distribution and environmental variables (Table 2, Fig. 2). A Monte Carlo test showed that both the first and second axes significantly fitted the environmental variables of the canonical axis (Monte Carlo test, $P < 0.05$). The first two

Table 1. Number of species, dominant species, and common species, in different watersheds.

Variable	Overall	River watershed			
		Han	Nakdong	Geum	Yeongsan–Seomjin
Total number of species	124	91	66	73	72
Number of endemic species	46	31	23	24	23
Number of exotic species	4	4	3	4	3
Dominant species (%)*	*Zacco platypus* (30.6)	*Z. platypus* (28.2)	*Z. platypus* (24.7)	*Z. platypus* (34.4)	*Z. platypus* (36.0)
Subdominant species (%)*	*Zacco koreanus* (11.6)	*Z. koreanus* (14.4)	*Z. koreanus* (14.8)	*Z. koreanus* (6.1)	*Z. koreanus* (10.3)
Most frequent species (%)**	*Z. platypus* (75.8)	*Z. platypus* (74.4)	*Z. platypus* (64.6)	*Z. platypus* (79.2)	*Z. platypus* (86.4)
Next most frequent species (%)**	*Pseudogobio esocinus* (46.0)	*Pungtungia herzi* (48.4)	*Opsariichthys uncirostris amurensis* (44.6)	*Pseudogobio esocinus* (71.5)	*Pungtungia herzi* (49.3)

* Percentage relative abundance. **Percentage of occurrence among the 720 study sites.

axes explained 7.4% of variance in species data and 62.5% of species–environment relationships. Among the 13 environmental variables tested, only 10 (BOD, altitude, stream order, water temperature, stream width, NO_3-N, pH, Chl.*a*, stream depth, and DO) were significantly correlated ($P < 0.05$) to axes 1 and 2 on forward selection, whereas the other three variables (TN, conductivity, and turbidity) were excluded from analysis ($P > 0.05$). Altitude was highly correlated with axis 1, and was negatively related to other physical factors (stream order and width, and water temperature), whereas BOD and NO_3-N were correlated with axis 2 (Table 2, Fig. 2).

Species such as *Orthrias nudus* (Bleeker), *Liobagrus andersoni* (Regan), *Rhynchocypris oxycephalus* (Sauvage and Dabry), and *Iksookimia koreensis* (Kim) inhabit the upper and upper-middle reaches of low-order streams at high altitude, where water temperature is low, whereas species such as *Sarcocheilichthys variegatus wakiyae* (Mori), *Opsariichthys uncirostris amurensis* (Berg), *Hemibarbus labeo* (Pallas), and *Acheilognathus yamatsutae* (Mori); and the exotic species *L. macrochirus* and *M. salmoides*; are principally found in the middle and lower reaches of wide streams of high order at low altitude, and thus at higher water temperatures. The species *Pseudorasbora parva* (Temminck and Schlegel), *C. auratus*, and *Cyprinus carpio* (Linnaeus), which tolerate water contamination, favor waters with a high BOD and NO_3-N, whereas Chl.*a* was associated with the distribution of *Hemiculter eigenmanni* (Jordan and Metz). The variables pH, DO, and stream depth showed relatively lower correlations with the two CCA axes. Overall, fish assemblages and explanatory variables were significantly correlated ($P < 0.01$ for the 1st canonical axis and the trace).

Longitudinal distribution of fish

To identify longitudinal distribution patterns, we evaluated the influence of altitude and stream order, as these variables showed strong associations with the 1st and 2nd CCA axes, respectively. Both of them showed dome-shaped relationship with mean number of species and mean number of endemic species. The mean total number of species per study site increased from the first-order (4.56 ± 0.43, mean $\pm$ SE) to fourth-order (9.79 ± 0.39) streams, and maintained an approximately similar number of species until the fifth (9.70 ± 0.48) order, then decreased at the sixth (8.43 ± 0.49) order ($r^2 = 0.9798$, $P < 0.01$, Fig. 3a). The mean number of endemic species per site also showed the similar pattern with the mean total number of species ($r^2 = 0.96$, $P < 0.01$, Fig. 3b). Altitude was classified into seven groups with 50 m interval, and the mean number of total species per site gradually increased until 250 m of altitude with the highest mean value of 10.38 (± 0.73 SE), while it decreased above 250 m ($r^2 = 0.81$, $P < 0.05$, Fig. 4a). The mean number of endemic species per site also showed similar

Table 2. Canonical and correlation coefficients of environmental variables with the first two axes of a CCA.

	Canonical coefficients		Correlation coefficients	
Variables	Axis 1	Axis 2	Axis 1	Axis 2
Stream order	0.095	– 0.310	0.230***	– 0.514***
Altitude	– 0.566	0.263	– 0.791***	0.282***
Stream width	0.097	– 0.163	0.286***	– 0.343***
Depth	0.066	– 0.109	0.002	– 0.125**
Water temperature	0.306	– 0.214	0.473***	– 0.383***
BOD	0.458	0.867	0.596***	0.729***
NO_3-N	– 0.011	– 0.123	0.268***	0.186***
Dissolved oxygen	– 0.131	0.033	– 0.066	– 0.103**
pH	– 0.193	0.019	– 0.168***	– 0.172***
Chl.*a*	0.123	– 0.135	0.376***	– 0.090*
Eigen value ($P < 0.01$)	0.315	0.223		

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

patterns with total number of species ($r^2 = 0.89$, $P < 0.05$, Fig. 4b).

Discussion

Relationship between fish distribution and environmental gradients

CCA modeling showed that fish were longitudinally distributed in a manner that correlated with the environmental gradient. Whereas BOD was correlated with axis 2 and the distribution of *P. parva*, *C. auratus*, and *C. carpio*, most physical variables (altitude, stream order, stream width, and water temperature), were more appropriately matched with fish distribution. As physical variables of streams are well correlated with fish distribution (Ibanez *et al.*, 2007); they can be used to predict the composition of local fish assemblages in Korea.

Kuehne (1962) studied the relationship between fish distribution and stream order; this correlation that has been frequently used when analyzing the longitudinal distribution of fish. Normally, the relationship between fish distribution and stream order is well matched with longitudinal fish distribution (Naiman *et al.*, 1987; Beecher *et al.*, 1988; Paller, 1994; Jang *et al.*, 2008), although exceptions have been reported (Hughes and Gammon, 1987; Hughes and Omernik, 1981, 1983). Although altitude alone can effectively predict fish distribution, a combination of altitude and stream order is more effective in this respect. In the present study, fish distribution in Korea was influenced by both stream order and altitude. The appropriate sampling method for first-order stream segments remains controversial (Matthews, 1998). To acquire meaningful data, we chose the point where discharge was maintained during sampling. Species numbers declined at sites in upper-stream reaches (altitude > 250 m) that were less than second order. This is attributable to habitat factors and the intrinsic characteristics of headwater streams. Thus, species such as *O. nudus*, *L. andersoni*, *R. oxycephalus*, *I. koreensis*, *Microphysogobio longidorsalis*, *Koreocobitis rotundicaudata*, and *Z. koreanus*, which are small, benthic fish, were abundant in such streams.

The greatest species diversity was found at 50–250 m in third- to fifth-order streams. This can be explained by both fish adaptability and habitat diversity. Most species in such watersheds are more adaptable than are those that inhabit headwaters; hence species abundance is greater. Moreover, a rise in habitat diversity, as reflected in substrate composition (Goldstein and Meador, 2005; Needbling and Quist, 2010) and aquatic plant variety (Diddle *et al.*, 1997), means that more fish species may be supported. Thus, the common observation that increasing habitat complexity changes the longitudinal distribution of fish species (Maturakis *et al.*, 1987; Kouamé *et al.*, 2008; Eitzmann and Paukert, 2010) is true of Korean streams.

In temperate streams, fish abundance gradually increases from the headwaters to the lower reaches (Horwitz, 1978; Schlosser, 1987; Penczak and Mann, 1990; Schlosser, 1990). However, in the present study, we found a small fall in total species numbers in the lower reaches. Oberdorff *et al.* (1993) reported similar results, and concluded that human activities negatively affected species diversity. It is also possible that our standard sampling method, especially our sampling equipment, was not appropriate for some larger streams. Consequently, fish diversity at some sites in lower stream reaches may have been underestimated. It may be necessary to use gill nets or fish traps in larger streams. Electrofishing would be effective, but use of this technique for quantitative research is prohibited by law. Streamside fishing is traditional in Korea (Jang *et al.*, 2005), and it is undesirable to electrofish in the presence of uninformed fishers as it might create the misunderstanding that electrofishing is legitimate. Thus, it is suggested that our sampling method is appropriate for streams less than 2 m in depth and that are of fourth order or below. Both this method and the use of gill nets and fixed nets are recommended for sampling of streams larger than the fifth order. To eliminate bias created by the use of various types of equipment, standardization of results is required. For example, the weighting of data acquired using different types of equipment may reduce data evaluation

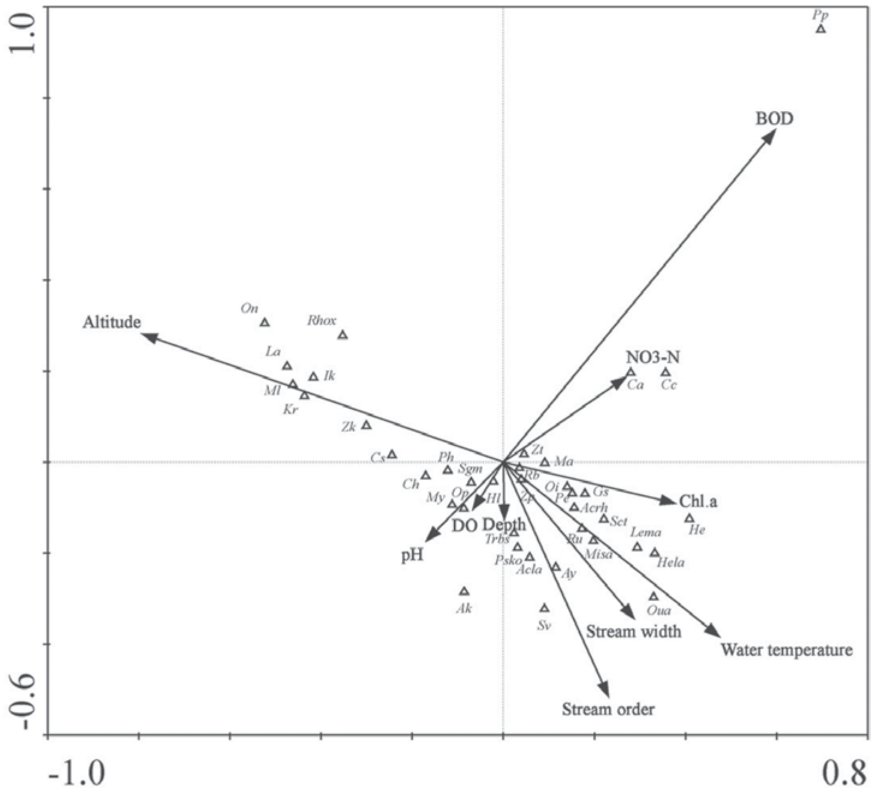

Fig. 2. Ordination plot from CCA correlating species presence with significant environmental variables. Acla, *Acheilognathus lanceolatus*; Acrh, *A. rhombeus*; Ak, *A. koreensis*; Ay, *A. yamatsutae*; Ca, *Carassius auratus*; Cc, *Cyprinus carpio*; Ch, *Coreoperca herzi*; Cs, *C. splendidus*; Gs, *Gnathopogon strigatus*; He, *Hemiculter eigenmanni*; Hela, *Hemibarbus labeo*; Hl, *H. longirostris*; Ik, *Iksookimia koreensis*; Kr, *Koreocobitis rotundicaudata*; La, *Liobagrus andersoni*; Lema, *Lepomis macrochirus*; Ma, *Misgurnus anguillicaudatus*; Misa, *Micropterus salmoides*; Ml, *Microphysogobio longidorsalis*; My, *M. yaluensis*; Oi, *Odontobutis interrupta*; On, *Orthrias nudus*; Op, *Odontobutis platycephala*; Oua, *Opsariichthys uncirostris amurensis*; Pe, *Pseudogobio esocinus*; Ph, *Pungtungia herzi*; Pp, *Pseudorasbora parva*; Psko, *Pseudobagrus koreanus*; Rb, *Rhinogobius brunneus*; Rhox, *Rhynchocypris oxycephalus*; Ru, *Rhodeus uyekii*; Sct, *Squalidus chankaensis tsuchigae*; Sgm, *S. gracilis majimae*; Sv, *Sarcocheilichthys variegatus wakiyae*; Trbs, *Tridentiger brevispinis*; Zk, *Zacco koreanus*; Zp, *Z. platypus*; Zt, *Z. temminckii*.

problems. Such weightings would have to be derived by field testing.

Status and conservation of fish

The fish species of each watershed were very similar. Few differences in species numbers were evident, and most species occurred in all watersheds, with the exception of *Gobiobotia naktongensis* (Mori) (absent from the NR), *K. rotundicaudata* (absent from the HR), and *Squaliobarbus curriculus* (Richardson) (absent from the HR and the GR), which were found in specific streams. We first considered whether such differences might be attributable to paleogeomorphological characteristics. The Korean peninsula is divided into three subregions, the west, south, and northeast. According to Lindberg (1972) and Nishimura (1974), the west and south are part of the Chinese subregion, whereas the northeast is part of the Siberian subregion. However, no great differences in fish communities were evident among subregions (Kim, 1995). Thus, other factors may explain the minor subregional differences observed. These include natural disturbance, stream piracy, flooding, anthropogenic activity, use of streams for water sports, local culture, and addition of aquarium fish to streams. More specifically, translocation of fish, whether intended or not, may also be in play. For example, species such as *O. uncirostris amurensis* and *Pseudobagrus fulvidraco* (Richardson) have been translocated from the NR to the GR and have come to dominate many sites. This accidently happened during translocation of commercial species like *P. fulvidraco* (Richardson) in early 1990s for increasing incomes of local fisherman in NR (personal communication with B.S. Chae). Over-predation by such species reduces the stability of the native fish community (Jang *et al.*, 2006). Therefore, management plans are needed to control and minimize the impact of introduced species. Currently in some aspect, introduced species are underestimated than exotic species because introduced also native within Korean peninsula. However, these are same with exotic between different river systems, and even more dangerous

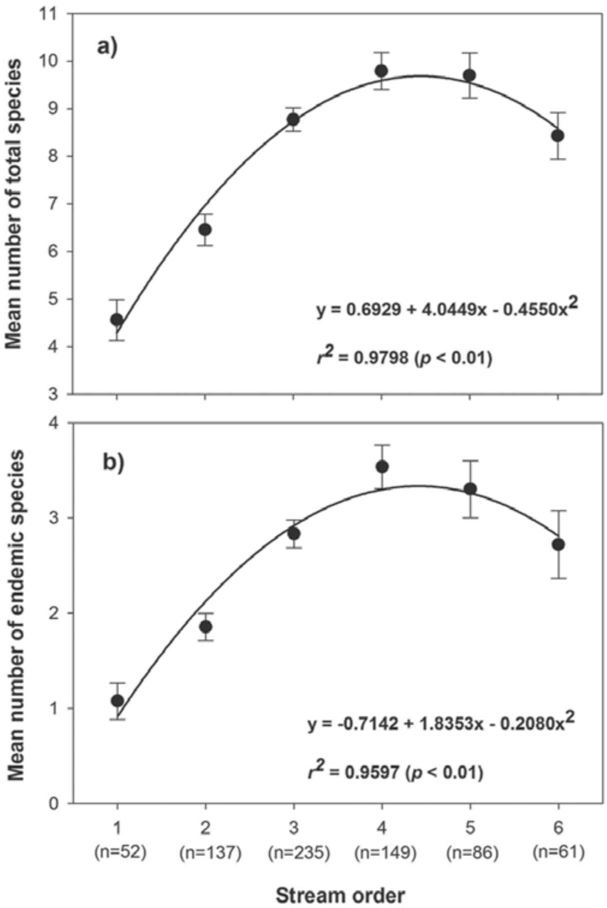

Fig. 3. Relationship between stream order and mean number of species (a), and mean number of endemic species (b) at different stream orders. The solid line showed regression by quadratic equation. Bar indicated the standard error of each stream order.

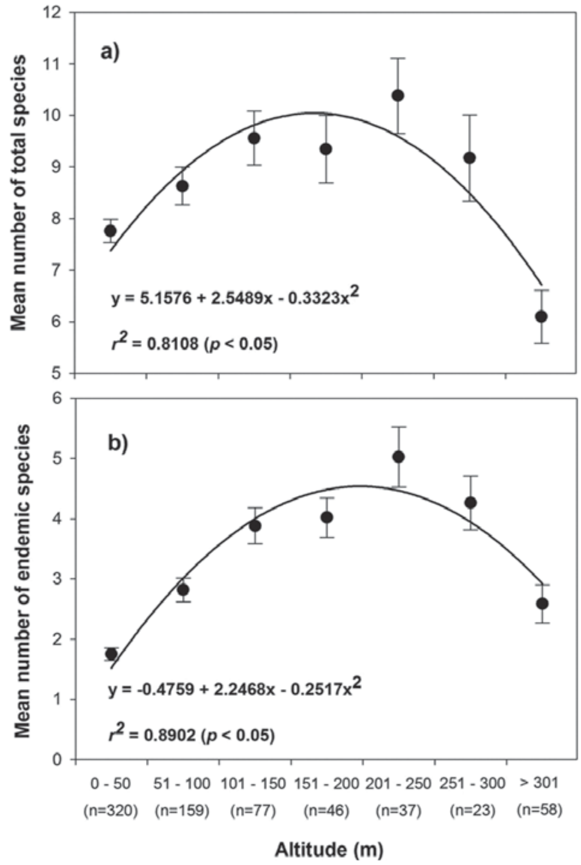

Fig. 4. Relationship between stream order and mean number of species (a), and mean number of endemic species (b) as a function of altitude with 50 m interval. The solid line showed regression by quadratic equation. Bar indicated the standard error of altitude in each category.

due to the lack of public awareness. Therefore, to maintain native fish community against the impact of these introduced species, management plans are needed.

The occurrence rates of exotic species in all watersheds were lower than that found by Jang *et al.* (2002). Although it is relatively difficult to directly compare rivers, because of variation in river location and the numbers of study sites on different rivers, the overall pattern indicates that exotic species are falling in numbers, indicating (at a minimum) that the number of exotic species may be stabilizing. However, the distribution range of *M. salmoides* has increased because of human recreational activity (sports fishing) and other factors. Consequently, a management plan is needed to protect native species. In the present study, endemism was estimated at 31.7%, which is higher than the values 25.9 and 23.6% calculated by Kim (1995) and Jang *et al.* (2003), respectively, revealing that the numbers of endemic species have increased and that such species appear to be stable. Until now, there are no references published related with impact of exotic and introduced species on endemic species in Korean streams. This is due to the habitat preference between endemic and both exotic and introduced species, and thus there are little chances to meet each other. Therefore, for effective conservation of endemic species in Korean streams, protections of watershed and catchment area are more important than others. Although fish can migrate, habitat destruction eventually leads to their extinction, indicating a need for designation of buffer zone and construction of fishway that was suggested by Jang *et al.* (2003) to prevent the collapse of fish communities that take into account the results of this and other studies that assessed stream connectivity and continuity.

In conclusion, 124 species of 27 families were identified, with *Z. platypus* and *Zacco koreanus* of the Cyprinidae found to be the dominant and subdominant species, respectively. Of all species, 46 (37.1%) were endemic and 4 (3.2%) exotic. Altitude and stream order were longitudinally related to species distribution. With increasing stream order, the numbers of both total and endemic species gradually rose until the fourth–fifth-order was attained, and fell in sixth-order streams. The current status of freshwater fish in Korea is uncertain. Conservation activities are needed to protect stable populations of native fish; such efforts should include the promulgation and enforcement of new legislation. Moreover, public awareness of endemic Korean fish must be elevated by education. Additionally, long-term sustainable management strategies for conservation of native fish fauna are required.

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References

Allan J.D., 1995. Stream Ecology: Structure and Function of Running Waters, Chapman & Hall, London, 404 p.

Balmford A., Bruner A., Cooper P., Costanza R., Farber S, Green R.E., Jenkins M., Jefferiss P., Jessamy V., Madden J., Munro K., Myers N., Naeem S., Paavola J., Rayment M., Rosendo S., Roughgarden J., Trumper K. and Turner R.K., 2002. Economic reasons for conserving wild nature. *Science*, *297*, 950–953.

Beecher H.A., Dott E.R. and Fernau R.F., 1988. Fish species richness and stream order in Washington State streams. *Environ. Biol. Fish.*, *22*, 193–202.

Belliard J., Boët P. and Tales E., 1997. Watershed and longitudinal patterns of fish community structure in the Seine River basin, France. *Environ. Biol. Fish.*, *50*, 133–147.

Bruton M.N., 1995. Have fish had their chips? The dilemma of threatened fishes. *Environ. Biol. Fish.*, *43*, 1–27.

Buisson L., Blanc L. and Grenouillet G., 2007. Modeling stream fish species distribution in a river network: the relative effects of temperature versus physical factors. *Ecol. Freshwater Fish*, *17*, 144–157.

Diddle E.D., Killgore K.J. and Harrel S.L., 1997. Assessment of fish-plant interactions, Miscellaneous paper A-96-6, U.S. Army Engineering Waterways Experiment Station, Vicksburg, 23 p.

Eaton A.D., Clesceri L.S., Rice E.W., Greenberg A.E. and Franson M.A.H., 2005. Standard Methods for the Examination of Water and Wastewater, 21st edn., American Public Health Association, Washington, DC, 1368 p.

Eitzmann J.L. and Paukert C.P., 2010. Longitudinal differences in habitat complexity and fish assemblages structure of a Great Plains river. *Am. Midl. Nat.*, *163*, 14–32.

Gauch H.G., 1982. Multivariate Analysis in Community Ecology, Cambridge University Press, New York, 320 p.

Gehrke P.C., Gilligan D.M. and Barwick M., 2002. Changes in fish community of the Shoalhaven River 20 years after construction of Tallowa dam, Australia. *River Res. Appl.*, *18*, 265–286.

Goldstein R.M. and Meador M.R., 2005. Multilevel assessment of fish species traits to evaluate habitat degradation in streams of the upper Midwest. *N. Am. J. Fish. Manage.*, *25*, 180–194.

Grenouillet G., Pont D. and Hérissé C., 2004. Within-basin fish assemblage structure: the relative influence of habitat versus stream spatial position on local species richness. *Can. J. Fish. Aquat. Sci.*, *61*, 93–102.

Habit E., Belk M.C. and Parra O., 2007. Response of the riverine fish community to the construction and operation of a diversion hydropower plant in central Chile. *Aquat. Conserv.*, *17*, 37–49.

Horwitz R.J., 1978. Temporal variability patterns and the distribution patterns of stream fishes. *Ecol. Monogr.*, *48*, 307–321.

Hughes R.M. and Gammon J.R., 1987. Longitudinal changes in fish assemblages and water quality in the Williamette River, Oregon. *Am. Fish. Soc.*, *116*, 196–209.

Hughes R.M. and Omernik J.M., 1981. Use and misuse of the terms watershed and stream order. *In*: American Fisheries Society of Warmwater Streams Symposium, 320–326.

Hughes R.M. and Omernik J.M., 1983. An alternative for characterizing stream size. *In*: Fontaine T.D. III and Barter S.M. (eds.), Dynamics of Lotic Ecosystems, Ann Arbor Science, Michigan, 87–101.

Ibanez C., Oberdorff T., Teugels G., Mamononekene V., Lavoué S., Fermon Y., Paugy D. and Toham A.K., 2007. Fish assemblages structure and function along environmental gradients in rivers of Gabon (Africa). *Ecol. Freshwater Fish*, *16*, 315–334.

Jackson D.A., Peres-Neto P.R. and Olden J.D., 2001. What controls who is where in freshwater fish communities – the roles of biotic, abiotic, and spatial factors. *Can. J. Fish. Aquat. Sci.*, *58*, 157–170.

Jang M.H., Kim J.G., Park S.B., Jeong K.S., Cho G.I. and Joo G.J., 2002. The current status of the distribution of introduced fish in large river systems of South Korea. *Int. Rev. Hydrobiol.*, *87*, 319–328.

Jang M.H., Lucas M.C. and Joo G.J., 2003. The fish fauna of mountain streams in South Korean national parks and its significance to conservation of regional freshwater fish biodiversity. *Biol. Conserv.*, *114*, 115–126.

Jang M.H., Cho G.I. and Joo G.J., 2005. The impact of unregulated fishing on the size distribution of a fish population in a temperate upland stream pool. *J. Freshwater Ecol.*, *20*, 191–193.

Jang M.H., Joo G.J. and Lucas M.C., 2006. Diet of introduced largemouth bass in Korean rivers and potential interactions with native fishes. *Ecol. Freshwater Fish*, *15*, 315–320.

Jang M.H., Yoon J.D., Shin J.H. and Joo G.J., 2008. Status of freshwater fish around the Korean Demilitarized Zone and its implications for conservation. *Aquat. Conserv.*, *18*, 819–828.

Kim I.S., 1995. The conservation and status of threatened freshwater fishes in Korea. *In*: Lee H.J. and Kim I.S. (eds.), Proceedings of Ichthyofauna and Characteristics of Fresh-Water Ecosystems in Korea, The Ecological Society of Korea and The Korean Society of Ichthyology, Seoul, 31–50.

Kim I.S. and Park J.Y., 2002. Freshwater Fish of Korea, Kyo-Hak Publishing, Seoul, 467 p.

Kouamé K.A., Yao S.S., Bi G.G., Kouamélan E.P., N'Douba V. and Kouassi N.J., 2008. Influential environmental gradients and patterns of fish assemblages in a West African basin. *Hydrobiologia*, *603*, 159–169.

Kouamélan E.P., Teugels G.G., N'Douba V., Bi G.G. and Koné T., 2003. Fish diversity and its relationships with environmental variables in a West African basin. *Hydrobiologia*, *505*, 139–146.

Kuehne R.A., 1962. A classification of streams, illustrated by fish distribution in an eastern Kentucky creek. *Ecology*, *43*, 608–614.

Lindberg G.U., 1972. Large-scaled fluctuation of sea level in the Quaternary Period, Nauka, Moscow, 760 p. (in Russian).

Martinez P.J., Chart T.E., Trammell M.A., Wullschleger J.G. and Bergersen E.P., 1994. Fish species composition before and after construction of a main stem reservoir on the White River, Colorado. *Environ. Biol. Fish.*, *40*, 227–239.

Matthews W.J., 1998. Patterns in Freshwater Fish Ecology, Chapman & Hall, New York, 784 p.

Matthews W.J. and Robison H.W., 1988. The distribution of the fishes of Arkansas: a multivariate analysis. *Copeia*, *1988*, 358–374.

Matthews W.J., Hough D.J. and Robison H.W., 1992. Similarities in fish distribution and water quality patterns in streams of Arkansas: congruence of multivariate analysis. *Copeia*, *1992*, 296–305.

Maturakis E.G., Woolcott W.S. and Jenkins R.E., 1987. Physiographic analyses of the longitudinal distribution of fishes in the Rappahannock River, Virginia. *Assoc. Southeast. Biol. Bull.*, *34*, 1–14.

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

Moyle P.B. and Cech J.J. Jr., 2000. Fishes: An Introduction to Ichthyology, 4th edn., Prentice Hall Inc., New Jersey, 744 p.

Naiman R.J., Melillo J.M., Lock M.A., Ford T.E. and Reice S.E., 1987. Longitudinal patterns of ecosystem processes and community structure in a subarctin river continuum. *Ecology*, *68*, 1139–1156.

Needbling T.E. and Quist M.C., 2010. Relationships between fish assemblages and habitat characteristics in Iowa's non-wadeable rivers. *Fish. Manage. Ecol.*, *17*, 369–385.

Nelson J.S., 1994. Fishes of the World, 3rd edn., John Wiley & Sons, New York, 624 p.

Nishimura S., 1974. Origin and History of the Japan Sea: An Approach from Biogeographic Standpoint, Tsukiji Shokan, Tokyo, 274 p. (in Japanese).

Oberdorff T., Guilbert E. and Lucchetta J.C., 1993. Patterns of fish species richness in the Seine River basin, France. *Hydrobiologia*, *259*, 157–167.

Oberdorff T., Pont D., Hugueny B. and Chessel D., 2001. A probabilistic model characterizing riverine fish assemblages of French rivers: a framework for environmental assessment. *Freshwater Biol.*, *46*, 399–415.

Paller M.H., 1994. Relationships between fish assemblage structure and stream order in South Carolina coastal plain streams. *Am. Fish. Soc.*, *123*, 150–161.

Penczak T. and Mann R.H.K., 1990. The impact of stream order on fish population in the Pilica drainage basin, Poland. *Pol. Arch. Hydrobiol.*, *37*, 243–261.

Ricciardi A. and Rasmussen J.B., 1999. Extinction rates of North American freshwater fauna. *Conserv. Biol.*, *13*, 1220–1222.

Sala O.E., Chapin F.S. III., Armesto J.J., Berlow R., Bloomfield J., Dirzo R., Huber-Sanwald E., Huenneke L.F., Jackson R.B., Kinzig A., Leemans R., Lodge D., Mooney H.A., Oesterheld M., Poff N.L., Sykes M.T., Walker B.H., Walker M. and Wall D.H., 2000. Global biodiversity scenarios for the year 2100. *Science*, *287*, 1770–1774.

Schlosser I.J., 1987. A conceptual framework for fish communities in small warm water streams. *In*: Matthews W.J. and Heins D.C. (eds.), Community and Evolutionary Ecology of North American Stream Fishes, University of Oklahoma Press, Norman, 17–24.

Schlosser I.J., 1990. Environmental variation, life history attributes, and community structure in stream fishes: implications for environmental management and assessment. *Environ. Mange.*, *14*, 621–628.

Strahler A.N., 1957. Quantitative analysis of watershed geomorphology. *Trans. Am. Geophys. Union*, *38*, 913–920.

Ter Braak C.J.F. and Šmilauer P., 2002. CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5), Microcomputer Power, Ithaca, 500 p.