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A study of low-temperature and mountain epilithic diatom community in mountain stream at the Han River system, Korea

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Abstract

Background: This study was conducted to assess the physicochemical water quality and the altitudinal distribution of low-temperature and mountain epilithic diatom (LTMD) community in Buk and Hangae streams that are located in Seorak Mountain with the height of 1708 m in Korea. And the community characteristics of LTMD found in the Buk and Hangae streams were compared to that of LTMD from the Han River system.

Results: The physicochemical water qualities of Buk and Hangae streams were determined to be very clean. As a result of analyzing the community composition, 135 taxa of epilithic diatoms were determined, and 22 taxa appeared including *Hannaea arcus* var. *subarcus* which are known to have low-temperature and mountain ecological characteristics in the literatures. The relative frequencies of LTMD were 37.0–0.9% range from the upper to lower regions. Although *Diatoma tenuis*, *Eunotia minor*, and *Gomphonema affine* are known to be ubiquitous in streams and lakes, in this research, the three taxa were added into low-temperature and mountain epilithic diatom, since *D. tenuis* and *E. minor* appeared only in altitudes above 600 m, and *G. affine* had the highest relative frequency during spring and fall in altitudes above 700 m, when water temperature was around 10 °C.

Conclusions: Among the 24 taxa of low-temperature and mountain epilithic diatom (LTMD) (including the 3 taxa added in this study), 14 taxa (*Diatoma hyemalis*, *D. mesodon*, *D. tenuis*, *Hannaea arcus*, *H. arcus* var. *subarcus*, *Ulnaria inaequalis*, *Eunotia bilunaris*, *E. implicata*, *E. minor*, *E. muscicola*, *E. silvahercynia*, *E. septena*, *Delicata delicatula*, and *Gomphonema affine*) represented the characteristics of LTMD very well; they grow best in water temperatures below 15 °C in Buk and Hangae streams and Han River system.

Keywords: Altitudinal distribution, Buk and Hangae streams, Epilithic diatom, Han River system, Low-temperature and mountain

Background

Mountain streams are fragile ecosystems (Kim et al. 2012; O'Driscoll et al. 2012), sensitive to human influences such as road construction and environmental changes such as those due to climate change (Lang and Murphy 2012). Species richness in these streams is usually limited by extreme environmental conditions (Chapin and Körner 1995) and communities are therefore particularly sensitive to disturbances. Because of their sensitivity, freshwater ecosystems in these areas are useful for biodiversity and biological indicator research. Diatoms are an

important component in these communities. However, although diatoms play key roles in inorganic nutrient cycling involving phosphorus and silica, studies have not been conducted on these diatoms due to accessibility and economic constraints (Loeb et al. 1983; Sánchez-Castillo et al. 2008).

Diatoms respond to changes in water quality, making them useful as biological indicators (Descy 1979; Watanabe et al. 1990). Diatoms also recover quickly after habitat disturbances, compared to other organisms (Descy 1979). Additionally, changes in their biomass can indicate shifts in other environmental metrics, such as feeding by herbivores, water temperature, substrate, nutrients, flow velocity, and flow rate (Allan 1995).

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Studies on diatoms in mountain streams have been conducted in the headwaters of montane to alpine regions in Canada (Antoniades and Douglas 2002; Lauriol et al. 2006), Russia (Potapova 1996; Medvedeva 2001), Poland (Kownacki et al. 2006), and Bolivia (Servant-Vildary 1982). Recently, studies related to climate change and biological water assessment have been conducted, including research on the integrity of freshwater ecosystems (Falasco et al. 2012), physicochemical factors of upland blanket peat catchments (O'Driscoll et al. 2012), aquatic ecosystem monitoring, and on monitoring the integrity of biological resources and habitats. Until now, the reported diatomic indices were developed through indexing nutrients and organic matter such as the trophic diatom index (TDI) or the diatom assemblage index to organic pollution (DAIpo); however, because high altitude streams generally have relatively clean water, Falasco et al. (2012) have suggested modifying the diatomic indicators.

In Korea, only research on fishes and benthic macroinvertebrates of mountain streams has been conducted (Chung et al. 2011; Son et al. 2011), and very little research has been done on epilithic diatoms (Kim et al. 2012). Currently in Korea, nationwide biological assessments of water quality are being performed. The sites of the biological assessments of water quality are mostly in mid-lower streams; thus, the research and monitoring of mountain stream are only being done in limited areas. In addition, the appropriate indicators and indices to monitor mountain streams have not been developed; research on community composition or habitat characteristics of epilithic diatoms is insufficient.

In this study, we investigated the epilithic diatom community and physicochemical water quality parameters in the Buk and Hanga streams, the highest altitude streams in the Han River system. We focused on the distribution of low-temperature and mountain epilithic diatoms according to temperature and altitude from the literature. The aims of our research were to (i) select the indicator species that can monitor mountain stream and (ii) evaluate the applicability of the selected indicator species.

Methods

Study areas and sampling sites

The 20 sites of investigation for this research were set every 100 m between the Buk and Hanga streams, which flow into Soyang Lake and the Soyang River on Seorak Mountain (1708 m). We sampled four times in the sampling site (total of 80 samples) from May to November 2011.

The Buk stream rises from Seorak Mountain, which is the highest mountain in Korea's Han River system. The Buk stream flows into Soyang Lake, joining the Soyang

River and the Naerin stream past Baekdam (573 m), Gugokdam (710 m), and Gayangdong Valley (778 m). The distance from Gayangdong Valley to the Soyang Dam (100 m) is 97 km, and 13 sites (BC01~BC13) were investigated between the two. The Hanga stream rises from Hangaeryung (881 m), passes through Hangaeryung Valley (764 m), Jangsudae (652 m), and Oknyutang (365 m), and flows into the Buk stream. The distance from Hangaeryung to the point where the Buk stream joins is 16 km, and seven sites (HG01~HG07) were investigated between the two points (Fig. 1).

The community characteristics of LTMD found in the Buk and Hanga streams were compared to that of LTMD from the Han River system. Data from the Han River system the research results of 19 sites (220–871 m) from Kim et al. (2012).

Sampling and analysis methods

The altitude at the sampling sites was measured by GPS (Triton, Magellan) and was also based on referenced data from the National Geographic Information Institute (www.ngii.go.kr). A portable meter (Horiba D-55, Orion 5-Star) was used to measure the physiochemical factors: water temperature, dissolved oxygen (DO), pH, conductivity, and turbidity in the field. Water velocity was measured by the Craig method (Craig 1987). Chlorophyll *a*, biological oxygen demand (BOD), total nitrogen (TN), and total phosphorus (TP) were analyzed by standard methods (Greenberg et al. 2000). Rock or gravel was selected 20–30 cm under the water surface for attached algae sampling. Rock (25–100 cm²) was brushed and scraped, and the scraped material was diluted in 300 ml distilled water. Samples were stored after fixation in Lugol's solution (Greenberg et al. 2000). Permanent slide samples were made for analysis of diatoms. Epilithic diatoms in the samples were identified using $\times 200$ to $\times 1000$ magnification under light and phase-contrast microscopy (Olympus BX41, Japan). Species were identified in accordance with Krammer and Lange-Bertalot (1986, 1988, 1991), Krammer (2002), Lange-Bertalot et al. (2010), Round et al. (1990) and AlgaeBase (www.algaebase.org).

Illustrations, including those by Joh et al. (2010), Chung (1993), Krammer (2002), Lange-bertalot et al. (2010), Round et al. (1990); and literature, including Antoniades and Douglas (2002), Kim et al. (2009), Lee et al. (1992), Medvedeva (2001), O'Driscoll et al. (2012), Torne's et al. (2012), were referenced to make the list of LTMD that live in low-temperature or mountainous areas.

Detrended correspondence analysis (DCA) and correlation analysis were performed to assess the relationships among the number of cells, relative frequency, physicochemical factors, and altitude ($n = 80$) using PC-ORD (MjM Software, Gleneden Beach, OR, USA) and SPSS ver. 12.0 software (SPSS, Inc., Chicago, IL, USA).

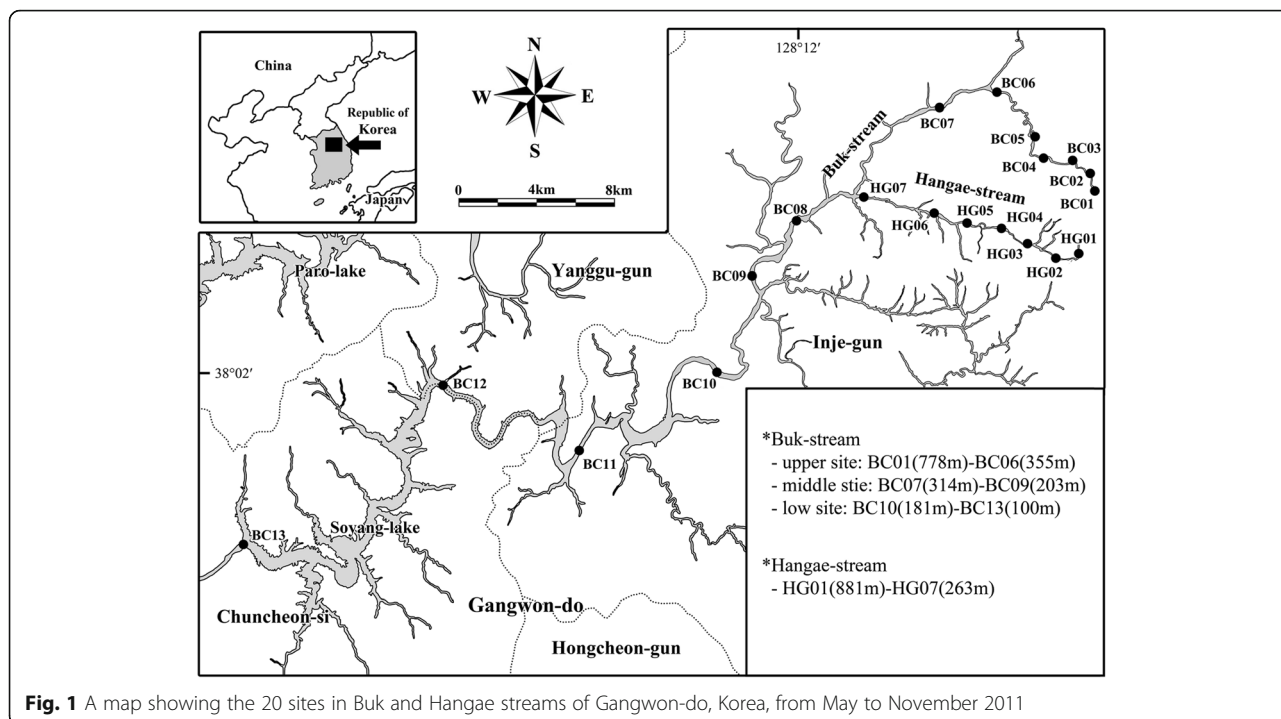


Fig. 1 A map showing the 20 sites in Buk and Hange streams of Gangwon-do, Korea, from May to November 2011

Results

Physicochemical factors

All physicochemical factors, excluding water temperature, were subdivided into upper, middle, and lower stream reaches based on altitude and habitat environment. All Hange stream sites were classified as upper stream reaches.

The water temperature in the Buk and Hange streams was 8.3–26.9 °C and increased as altitude decreased (Fig. 2). The greatest difference between the highest and lowest water temperature in the Buk stream was measured in May, and the least difference was measured in August. Water temperatures at sites

BC01 to BC04, with an average altitude of 500 m or greater, averaged < 15 °C, decreasing by 1.4 °C ($r^2 = 0.893$) per 100 m of altitude. In contrast, the greatest and least differences between the highest and lowest water temperatures were measured in August and November, respectively, in the Hange stream. The average water temperature was < 15 °C from HG01 to HG04, sites with elevations of > 500 m. For every 100 m increase in elevation, water temperature dropped by 1.1 °C ($r^2 = 0.964$). The pH of the Buk stream was slightly acidic at 6.5, whereas the Hange stream had a pH of 7.4–8.0. The conductivity in the upper part of the Buk stream was very low with an average of

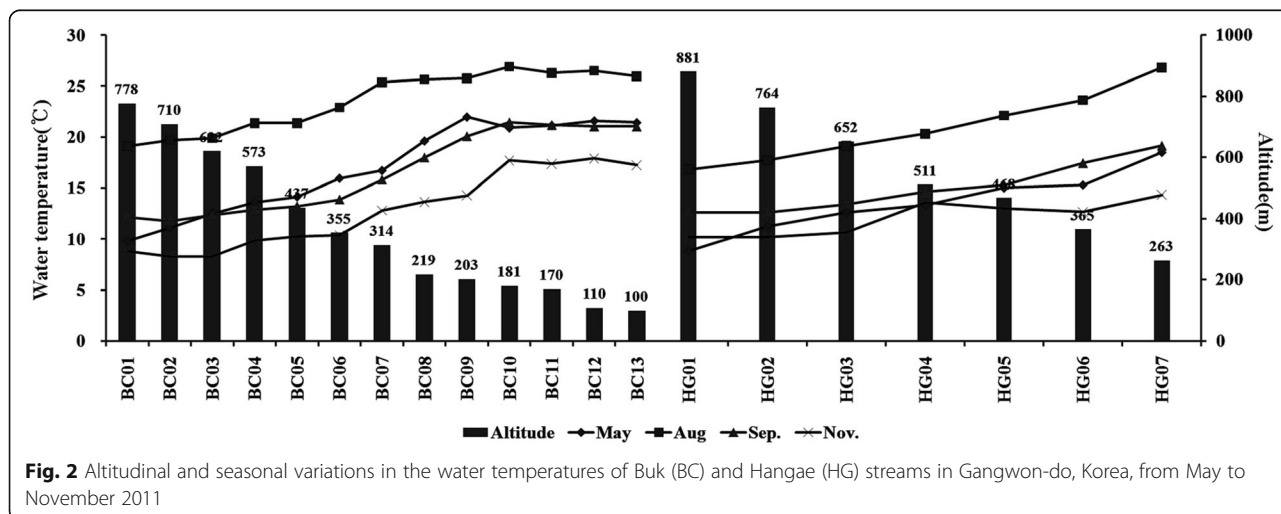


Fig. 2 Altitudinal and seasonal variations in the water temperatures of Buk (BC) and Hange (HG) streams in Gangwon-do, Korea, from May to November 2011

25.9 $\mu\text{S cm}^{-1}$. The middle and lower stretches of the Buk and Hangae streams had low conductivity of 60 $\mu\text{S cm}^{-1}$. Chlorophyll *a* concentration in the lower Buk stream was 13.3 $\mu\text{g L}^{-1}$. In other sites, the concentration was low, averaging $\leq 1 \mu\text{g L}^{-1}$. The water quality was clean with an average DO consumed in 5 days (BOD_5) of $\leq 2 \text{ mg L}^{-1}$ at all sites. The average TN was 1.283–1.891 mg L^{-1} and did not show much seasonal variation. TP was 17.1–22.1 $\mu\text{g L}^{-1}$, increasing downstream (Table 1).

Altitude was highly correlated with velocity ($r = 0.73$), pH ($r = -0.66$), water temperature ($r = -0.64$), and TP ($r = -0.55$). Chlorophyll *a* showed an extremely high correlation with turbidity ($r = 0.82$) and a high correlation with TP. TN was correlated with conductivity and turbidity but not with other physicochemical factors (Table 2).

Community composition and LTMD

A total of 135 epilithic diatom taxa were identified in the Buk and Hangae streams. The least number of taxa (10–12) were found in the Hangae stream and the upper Buk stream. An average of 22 and 21 taxa appeared in the middle and lower stretches of the Buk stream, respectively. Site BC08, in the middle of the stream, showed the most diversity with 33 taxa collected in May. The number of taxa decreased at site BC10, at the inlet of Soyang Lake (Fig. 3).

From the literature in Korea, low-temperature and mountain-dwelling algae of 39 taxa were identified. Of these 39 taxa, 32 taxa were diatoms, 5 taxa were Cryso-phyceae, and 2 taxa were Chlorophyceae. Of the 32 taxa of diatoms in Korea, 21 taxa appeared in this study. These include *Diatoma hyemalis*, *D. mesodon*, *D. moniliformis*, *Hannaea arcus*, *H. arcus* var. *subarcus*, *Ulnaria inaequalis*, and *Tabellaria flocculosa* in Fragilariaceae;

Eunotia bilunaris, *E. implicata*, *E. muscicola*, *E. silva-hercynia*, and *E. septena* in Eunotiaceae; *Eucoconeis laevi* and *Planothidium lanceolatum* of Achnantheaceae; and *Cymbella aspera*, *C. leptoceros*, *C. tumida*, *Delicata delicatula*, *Reimeria sinuata*, *Gomphonema acuminatum*, and *G. clavatum* in Naviculaceae. Additionally, *Diatoma tenuis*, *Eunotia minor*, and *Gomphonema affine* were classified as LTMD due to their limited appearance at altitudes $> 500 \text{ m}$. The relative frequencies of LTMD ranged from 0.0 to 94.6%, appearing more frequently in altitudes $> 500 \text{ m}$ (Fig. 4).

The five *Eunotia* species usually appeared at altitudes of $> 500 \text{ m}$; in particular, *E. septena* and *E. implicata* were limited to altitudes $> 700 \text{ m}$. *Gomphonema affine* showed a similar trend to that of *Eunotia* with a high relative frequency at altitudes $> 700 \text{ m}$ and a decreasing relative frequency below 600 m. It also showed decreasing relative frequency in summer and increasing frequency in spring and fall (Fig. 5).

Hannaea arcus and *H. arcus* var. *subarcus* showed differences in habitat range. The appearance of *H. arcus* was limited to altitudes of 200–300 m, whereas *H. arcus* var. *subarcus* showed its highest relative frequency at 400 m, and decreased in either the upper or lower parts of the streams. *Ulnaria inaequalis* had high relative frequency at about 300 m and showed a similar range to that of *H. arcus*. *Ulnaria inaequalis* and *H. arcus* had a high relative frequency during spring, when they appeared at $< 200 \text{ m}$ (Fig. 5).

Similar to *Eunotia*, *Diatoma hyemalis* only appeared in altitudes $> 700 \text{ m}$, whereas *D. tenuis* was limited to about 600 m. *D. mesodon* only appeared at altitudes $> 700 \text{ m}$ during summer when water temperature was high and appeared at around 300 m in the fall and spring (Fig. 5). Excluding *Delicata delicatula*, most taxa in Cymbellaceae appeared at low altitudes. Regardless of

Table 1 Mean values of physicochemical factor values in Buk (BC) and Hangae (HG) streams of Gangwon-do, Korea, from May to November 2011

Parameter	Buk stream (mean \pm SD)			Hangae stream (mean \pm SD)
	Upper (BC01–06)	Middle (BC07–09)	Lower (BC10–13)	
Altitude (m)	579.2 \pm 160.6	351.2 \pm 60.0	185.9 \pm 41.2	503.8 \pm 219.9
Velocity (cm s^{-1})	65.8 \pm 19.5	35.0 \pm 16.1	13.7 \pm 12.8	54.6 \pm 4.8
Dissolved oxygen (mg L^{-1})	9.3 \pm 2.1	9.1 \pm 0.1	10.1 \pm 0.3	8.8 \pm 0.4
pH	6.5 \pm 0.4	7.8 \pm 0.7	8.0 \pm 0.1	7.4 \pm 0.2
Conductivity ($\mu\text{S cm}^{-1}$)	25.9 \pm 4.2	61 \pm 12.8	60.9 \pm 6.3	64.1 \pm 19.4
Turbidity (NTU)	0.8 \pm 1.0	1.2 \pm 1.2	12.0 \pm 4.1	0.6 \pm 0.6
Chlorophyll <i>a</i> ($\mu\text{g L}^{-1}$)	0.2 \pm 0.1	1.2 \pm 0.4	13.3 \pm 5.6	0.6 \pm 0.2
BOD_5 (mg L^{-1})	0.6 \pm 0.1	1.6 \pm 1.0	2.0 \pm 0.8	0.5 \pm 0.0
Total nitrogen (mg L^{-1})	1.386 \pm 0.140	1.283 \pm 0.138	1.891 \pm 0.152	1.323 \pm 0.302
Total phosphorus ($\mu\text{g L}^{-1}$)	17.7 \pm 8.3	22.1 \pm 3.4	49.5 \pm 6.7	17.1 \pm 1.1

Table 2 Correlation comparison of physicochemical factors in Buk (BC) and Hangae (HG) streams of Gangwon-do, Korea, from May to November 2011

	WT	DO	pH	EC	Tur.	Chl. <i>a</i>	BOD ₅	TN	TP	Altitude	Velocity
WT	1.00	-0.29**	0.57**	0.15	0.51**	0.44**	0.44**	0.03	0.49**	-0.64**	-0.51**
DO		1.00	0.20	0.19	0.14	0.07	0.04	0.07	0.00	-0.28*	-0.24*
pH			1.00	0.46**	0.44**	0.43**	0.35**	0.15	0.41**	-0.66**	-0.62**
Con.				1.00	0.07	0.00	0.09	0.40**	0.03	-0.40**	-0.36**
Tur.					1.00	0.82**	0.57**	0.35**	0.55**	-0.39**	-0.41**
Chl. <i>a</i>						1.00	0.45**	0.21	0.56**	-0.38**	-0.44**
BOD ₅							1.00	0.09	0.40**	-0.38**	-0.30**
TN								1.00	-0.02	-0.02	-0.16
TP									1.00	-0.55**	-0.60**
Altitude										1.00	0.73**
Velocity											1.00

WT water temperature, DO dissolved oxygen, EC electric conductivity, Tur. turbidity, TN total nitrogen, TP total phosphorus
 * $P < 0.05$, ** $P < 0.01$, $n = 80$

season, the relative frequency of *Reimeria sinuata* appeared in altitudes 200 m. *Cymbella tumida* did not show a relationship with altitude or water quality, appearing at altitudes < 300 m. Along with *Reimeria sinuata*, *Planothidium lanceolatum* showed the highest relative frequency at altitudes of 200 m (Fig. 5).

DCA was conducted by assigning all LTMD and all other species with a relative frequency higher than 1% to a main matrix, and assigning physicochemical factors to the second matrix. As a result, the eigenvalue of axis 1 was 0.599 and was highly correlated with factors such as water temperature, pH, TP, and BOD₅, but was negatively correlated with altitude ($r = -0.809$) and velocity ($r = -0.747$). The eigenvalue of axis 2 was 0.346, and it was positively correlated with water temperature, pH, and conductivity but negatively correlated with altitude (Fig. 6).

In the graph, taxa with positive values on axis 1 show increased relative frequency when the altitude and water

velocity decreased and the water temperature increased. These taxa had the greatest correlation to changes in physicochemical factors such as pH, BOD₅, and TP. The taxa on the positive side of axis 2 are those in which relative frequencies increased as pH increased. Taxa on the negative side of axis 2 decreased in relative frequency as pH increased. Therefore, taxa placed in the third quadrant best represent the characteristics of LTMD (Fig. 6).

LTMD at other mountain streams in the Han River system (Kim et al. 2012)

The average water temperature of the streams in the Han River system was 14.5 °C, which shows the weak relationship between altitude and water temperature ($r^2 = 0.106$). The relationship between altitude and water temperature seems to be greater in an area where the riverbed is rarely changed, and in riparian vegetation

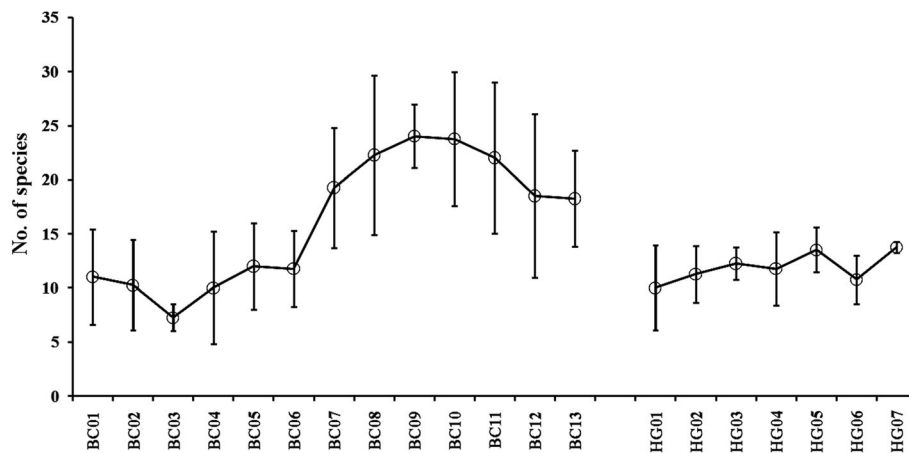


Fig. 3 The species numbers of epilithic diatom in Buk (BC) and Hangae (HG) streams of Gangwon-do, Korea, from May to November 2011

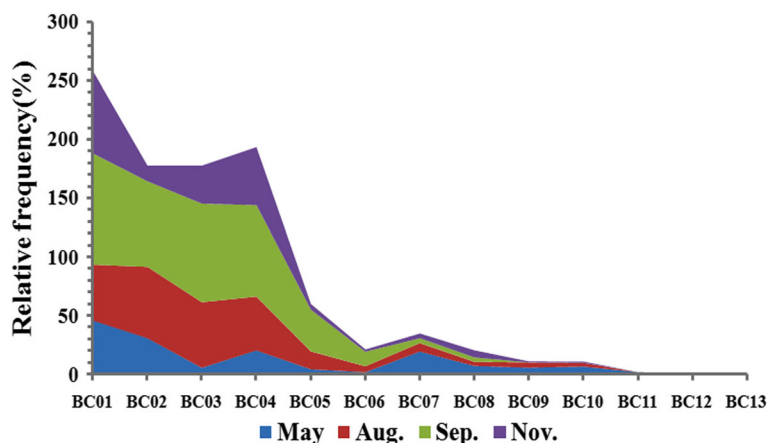


Fig. 4 Relative frequency of LTMD in Buk stream of Gangwon-do from May to November 2011

environments, such as the Buk and Hangae streams (Kim et al. 2012). The pH ranged from 6.8 to 9.5, with a large variation, depending on the area. A total of 14 taxa of LTMD were found, including *Cymbella affine*, *C. tumida*, *Diatoma mesodon*, *D. vulgare*, *Eunotia minor*, *E. pectinalis*, *Hannaea arcus*, *H. arcus* var. *subarcus*, *Planothidium lanceolatum*, *Psammothidium oblongellum*, *Reimeria sinuata*, and *Ulnaria inaequalis*. The relative frequencies of LTMD ranged from 2.1 to 80.9%, with a high average of 33.9% at sites where water temperature

was 15 °C or less; the site S6 had the highest relative frequency, at 80.9%. The relative frequency of *Hannaea arcus* var. *subarcus* at site S6 was 56.6%; *H. arcus* var. *subarcus* showed the highest relative frequency among the LTMD ranging from 27.1 to 40.5% Fig. 7.

Discussion

Physicochemical factors

Of the physicochemical environmental factors examined, water temperature, pH, TP, and velocity were found to

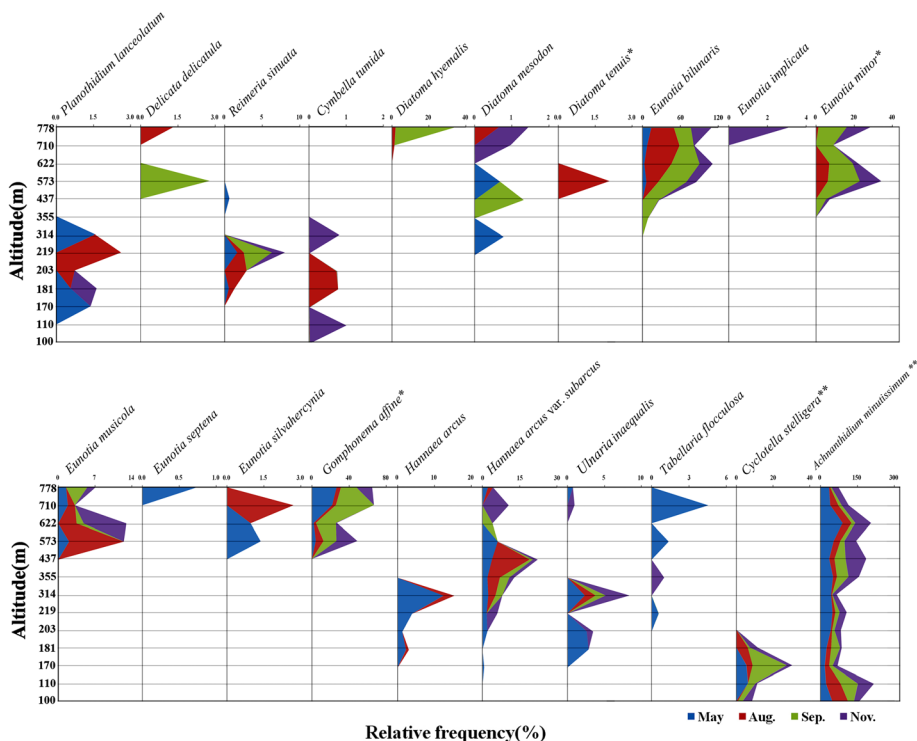
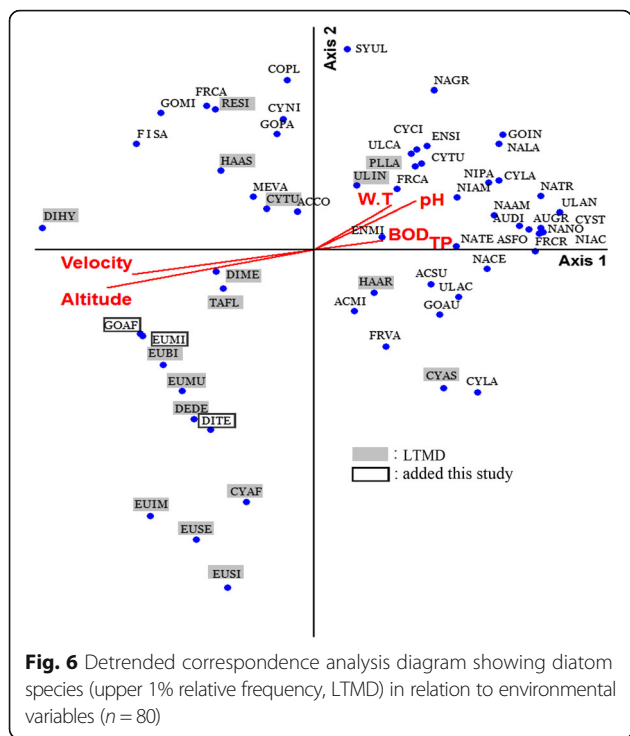


Fig. 5 The distribution of LTMD in Buk stream of Gangwon-do, Korea, from May to November 2011 (*added in this study, **taxa of widespread and lower altitude)



Community composition and LTMD

The 135 taxa of epilithic diatoms from the Buk and Hangae streams were similar to the 138 taxa found in high altitude streams in the Maritime Alps National Park (Falasco et al. 2012). The taxa that appeared in the upper region were not diverse. An increase in taxa due to nutrients (TP and TN), pH, and water temperature was observed beginning in the middle sections of the streams. Among the Pennales, diatoms in Naviculaceae and Fragilariaceae families were most diverse. In the upper region, saproxenous taxa (Watanabe et al. 2005) including *Encyonema minutum*, *Hannaea arcus* var. *subarcus*, and *Diatoma mesodon* were detected. In the middle and lower parts of the streams, the abundance of saprophilous taxa (Kelly and Whitton 1995; Watanabe et al. 2005) such as *Nitzschia amphibian*, *N. palea*, and *Navicula gregaria* of Naviculaceae and Bacillariaceae increased. Generally, the relative frequency of taxa in *Navicula* and *Nitzschia* were higher in the lower regions than those in the upper regions (Atazadeh et al. 2007; Kim et al. 2009), which was thought to be due to pH and nutrient concentrations (Ginn et al. 2007; Passy, 2007).

have strong relationships with altitude. For the Buk and Hangae streams, the change in factors such as water temperature, pH, and velocity can be sorted based on altitude of 500 m. Based on the altitude of 500 m, water temperature fluctuated around 15 °C, pH ranged from neutral to slightly acidic, and velocity showed about 30 cm s⁻¹ difference. The TP was greater in lower sites and showed little difference in concentration at upper and middle sites (Table 1).

The negative correlation between altitude and water temperature can only be applied to streams with ecologically similar environments (Kim et al. 2012), because they are affected by groundwater and riparian vegetation. Complementary data are needed for each ecological environment to compare between streams.

Among the 32 taxa of mountain diatoms in Korea, 21 taxa were identified in this study, and 3 additional taxa were added. The genus *Eunotia* best represented the characteristics of LTMD. Most taxa in the genus *Eunotia* appear in low pH, alpine headwaters (Joh et al. 2010, Lange-Bertalot et al. 2010). This is thought to be due to the greater effect of pH than water temperature on this genus. *Eunotia implicata* was limited to altitudes > 700 m (Fig. 5). The seasonal average pH was slightly acidic at ≤ 6.5 (Table 1). *Eunotia bilunaris* had a decreasing relative frequency starting at an altitude of 500 m, and did not appear at 300 m, where the pH was 7.0. All *Eunotia* taxa were placed in the third quadrant of the DCA chart, which means they appeared in the high altitude, low-pH environment (Fig. 6). The seven taxa of *Eunotia* including *E. minor* showed these characteristics clearly. The newly added LTMD from this study,

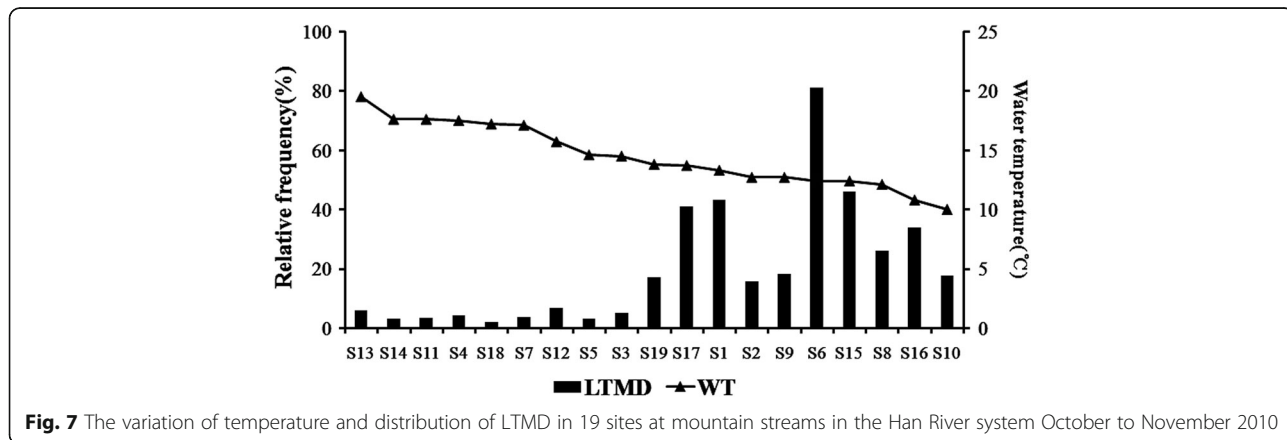


Fig. 7 The variation of temperature and distribution of LTMD in 19 sites at mountain streams in the Han River system October to November 2010

Gomphonema affine and *D. teunis*, showed trends similar to those of *Eunotia*. In particular, during each of the four samples, *G. affine* showed less than 10% frequency only in August, when the water temperature was high. In altitudes above 700 m, the frequency of appearance of *G. affine* did not significantly differ, based on factors such as pH, water velocity, TN, and TP; its growth seems to be limited by water temperature.

Hannaea arcus appears as a major dominant species in the Sophia River and Sophia Lake in Canada (Antoniades and Douglas 2002). Sophia Lake and its catchment area are a low temperature water system (4–11 °C), located at the most northern part of Cornwallis Island (75° 06' N, 93° 36' W). *H. arcus* appears at 15 sites in the Sophia River and Sophia Lake catchment area, and has a high negative correlation with water temperature ($r^2 = 0.710$). The dominance ratio changes greatly with water temperature. Although *H. arcus* was detected in the present study at relatively low altitudes of 200–300 m, it was mostly in May, when the water temperature was about 15 °C. Growth of this genus was inhibited in the Buk stream, where pH was ≤ 7.0 and altitudes were > 300 m, which contrasted with the Antoniades and Douglas (2002) study, where it was found in water with a pH of around 8.0.

Hannaea arcus var. *subarcus*, a variety of *H. arcus*, was detected at the highest altitudes and had its greatest relative frequency at 400 m. The presence of this species was positively correlated with altitude ($r^2 = 0.539$) and negatively correlated with water temperature ($r^2 = 0.338$) in a study by Kim et al. (2012). *H. arcus* var. *subarcus*, along with *H. arcus*, clearly exhibited the characteristics of LTMD. *H. arcus* var. *subarcus* seems to have greater growth range compared to that of *H. arcus*.

Ulnaria inaequalis, of the family Fragilariaceae, showed similar trends to those of *H. arcus*, although it seemed to have a greater growth range compared to that of *H. arcus*. *Diatoma hyemalis* and *D. tenuis* were detected in similar locations as those of *Eunotia*, with limited appearance in the upper regions of the streams. *Diatoma hyemalis* is usually found in alpine low-temperature and oligotrophic water systems (Joh et al. 2010) such as in Switzerland (Robinson et al. 2010). *Diatoma mesodon* appeared at altitudes of 300–600 m during the spring and fall, and was seen at the highest altitude site in the summer and fall. *Diatoma mesodon*, as a representative mountain diatom along with *H. arcus*, is the dominant species in the Colorado River (Vavilova and Lewis 1999), the Willamette River in Oregon (Carpenter and Waite 2000), the Swiss Alps in Switzerland (Robinson and Kawecka 2005), and the Tatra River in the National Park of Poland (Kawecka and Robinson 2008). *Delicata delicatula* is usually found in oligotrophic mountains (Chung 1993) and was found in the upper region of the Buk stream during the summer and fall (Fig. 5). It was identified at the highest site during the summer and found at 600 m during the fall. *Delicata delicatula* was located near *E. bilunaris* and *E. musicola* on the DCA diagram; its range of growth seemed to be limited by pH.

Every epilithic diatom community found in streams has different characteristics due to differences in physicochemical factors, including velocity, riverbed, turbidity, flow rate, habitat environment, pH, conductivity, and nutrient concentrations. In the case of the Buk and Hangae streams, the physicochemical factors that affected the epilithic diatom community the most were altitude, water temperature, pH, and TP (Fig. 7). The

Table 3 The list of low temperature and mountain diatoms (LTMD) and ecological character which appeared in this study

Taxa	Code	Altitude	Season	Trophic state	Habitat character
<i>Delicata delicatula</i>	DEDE	U/M/L	S/Su/A/W	Oligo	Mt
<i>Diatoma hyemalis</i>	DIHY	U	Su/A	Oligo	Low pH/Mt
<i>Diatoma mesodon</i>	DIME	U/M/L	S/Su/A/W	Oligo/Meso/Eu	Mt/Lt
<i>Diatoma tenuis</i>	DITE	U/M	W	Oligo/Meso	Mt
<i>Eunotia bilunaris</i>	EUBI	U/M	S/Su/A/W	Oligo/Meso	Low pH/ Mt
<i>Eunotia minor</i>	EUMI	U/M	Su/A/W	Oligo/Meso	Lt
<i>Eunotia musicola</i>	EUMU	U	S/Su/A/W	Oligo/Meso	Mt
<i>Eunotia implicate</i>	EUIM	U/M/L	W	Oligo	Low pH/Mt
<i>Eunotia silvahercynia</i>	EUSI	U	S/A	Oligo	Low pH/Mt
<i>Eunotia septena</i>	EUSE	U/M	S	Oligo	Mt
<i>Gomphonema affine</i>	GOAF	U	S/Su/A/W	Oligo/Meso	Low pH/Mt
<i>Hannaea arcus</i>	HAAR	M/L	S/Su	Meso/Eu	pH 7.0~8.5/Lt
<i>Hannaea arcus</i> var. <i>subarcus</i>	HAAS	U/M/L	S/Su/A/W	Oligo/Meso/Eu	Lt
<i>Ulnaria inaequalis</i>	ULIN	M/L	S/Su/A/W	Meso/Eu	pH 7.0~8.5/Lt

U upper, M middle, L low, S spring, Su Summer, A autumn, W winter, Mt mountain, Lt low temperature

relative frequencies of LTMD were 37, 5.6, and 0.9% from the upper, middle, and lower regions, respectively (Fig. 4). The average relative frequency was $\geq 50\%$ at altitudes > 700 m. Additionally, LTMD appeared in the upper region, which is to be expected, as *Eunotia bilunaris*, *E. implicata*, *H. arcus*, *Diatoma hyemalis*, *D. mesodon*, *D. tenuis*, and *Tabellaria flocculosa* also appear as dominant species in high altitude streams from places such as Italy (Falasco et al. 2012), Canada (Antoniades and Douglas 2002), and Ireland (O'Driscoll et al. 2012).

Among the LTMD, *H. arcus*, *H. arcus* var. *subarcus*, *D. mesodon*, and *S. inaequalis* had similar frequency of occurrence in 19 sites at mountain streams of the Han River system, in the Buk and Hangae streams. Although a direct comparison of genus *Eunotia* was difficult due to low abundance, most appeared in upper streams of 19 sites in mountain streams. Genus *Cymbella* did not demonstrate the general characteristics of LTMD in either the Buk and Hangae streams, or mountain streams of the Han River system.

Conclusions

Among the 24 taxa of LTMD (excluding the 10 taxa with low occurrence tendencies and relative frequencies, such as genus *Achnanthes* and *Cymbella*), 14 taxa represented the characteristics of LTMD very well; they grow best in water temperatures below 15 °C. These are *Diatoma hyemalis*, *D. mesodon*, *D. tenuis*, *Hannaea arcus*, *H. arcus* var. *subarcus*, *Ulnaria inaequalis*, *Eunotia bilunaris*, *E. implicata*, *E. minor*, *E. muscicola*, *E. silvahercynia*, *E. septena*, *Delicata delicatula*, and *Gomphonema affine* (Table 3).

In all, *Hannaea arcus* var. *subarcus* was found in most mountain streams; it is thought to be a useful taxon as the most representative of Korean LTMD. The occurrence of five species in the genus *Eunotia* were found to have a more significant relationship to pH than to water temperature. Therefore, they were not useful as indicator species. However, if physicochemical factors such as oligotrophy, low conductivity, and weakly acidic pH are considered the primary characteristics of mountain streams or headwaters, the *Eunotia* species could be used as indicators. Although *Hannaea arcus* and *D. mesodon* are representative of the mountain-based epilithic diatom genera found in Korea and international studies, they can be useful as indicators for increases in water temperature; however, more studies are needed to identify additional ecological characteristics. More diverse indicators are needed to obtain accurate results monitoring mountain streams using LTMD.

Abbreviations

DCA: Detrended correspondence analysis; LTMD: Low-temperature and mountain epilithic diatom

Acknowledgements

Not applicable.

Funding

This research was supported by the foundation research project of National Research Foundation of Korea (2011–0005974).

Availability of data and materials

Please contact author for data requests.

Authors' contributions

KYJ carried out the design of the study, performed the fieldwork, and drafted the manuscript. LOK participated in the design and coordination of manuscript and helped draft the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 16 April 2017 Accepted: 2 August 2017

Published online: 15 August 2017

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