The Effect of Monsoon Rainfall Patterns on Epilithic Diatom Communities in the Hantangang River, Korea

In-Hwan Cho [1], Ha-Kyung Kim [1], Min-Hyuk Lee [2], Yong-Jae Kim [3], Hyuk Lee [4] and Baik-Ho Kim [5],*

[1] Department of Environmental Science, Hanyang University, Seoul 04763, Korea; crice5237@naver.com (I.-H.C.); hosang9022@naver.com (H.-K.K.)

[2] Doohee Institute of Ecological Research, Korea Ecosystem Service Inc., Gyeonggi-do 13814, Korea; angelchaser@nate.com

[3] Department of Life Science, Daejin University, Pochun, Gyunggi 487-711, Korea; yjkim@daejin.ac.kr

[4] National Institute of Environmental Research, Incheon 22689, Korea; ehyuk72@korea.kr

[5] Department of Life Science and Research Institute for Natural Sciences, Hanyang University, Seoul 04763, Korea

* Correspondence: tigerk@hanyang.ac.kr; Tel.: +82-2-2220-0960

Abstract: Most of Korea's rivers and lakes are subject to physico-chemical disturbances, such as increased water quantity and flow rates, and influx of nitrogen and phosphorus, due to intense rainfall concentrated in the Asian monsoon season. To examine the influence of rainfall on epilithic diatom communities, we measured the diatom distribution and river water quality at 29 sites along the main-stream and tributaries of the Hantangang River, Korea, in the period of 2012–2015. Water quality parameters in the polluted sites had improved following rainfall, but the response of dominant species varied with water quality; the dominant species *Nitzschia fonticola* decreased in abundance regardless of sampling sites, and the abundance of *Achnanthidium minutissimum* in the clean sites and *Nitzschia palea* in the polluted sites increased after rainfall, respectively. The community dynamic index (CDI) showed that the most obvious shift of epilithic diatom community occurred in the mid-polluted sites in 2013 with the highest rainfall. This suggest that the effect of rainfalls on the epilithic diatom community is dependent on various parameters, such as the magnitude of rainfall, water quality and its biotic compositions of diatom communities, but it also indicates that improving the water quality of rivers is important to promote the resilience of diatom communities to extremes of precipitation. Further investigation is needed to generalize the effects of monsoon rainfall on the epilithic diatom communities, considering rivers with different environmental characteristics.

Keywords: Asia-monsoon; community dynamic index; distance method; principal component analysis; epilithic diatom; rainfall; water quality

1. Introduction

The Asia-monsoon, also called the seasonal wind, refers to a change in wind direction in summer and winter driven by temperature differences between the land and ocean. Monsoons are associated with intense rainfall and are typically generated by seasonal changes in wind and atmospheric pressure. As a peninsula, South Korea is largely affected by the difference in heat capacity between the land and ocean; it is therefore influenced by seasonal wind, with a dominant northwesterly wind in winter and a dominant southeasterly wind in summer [1]. The Korean peninsula is mainly affected by the North Pacific High in summer, and more than 50% of the annual precipitation is concentrated within the monsoon season [2].

Due to rapid global climate change, the frequency of floods and droughts is becoming more irregular in the Korean peninsula and worldwide, with increasing impacts on the hydrology of rivers and lakes [3–5]. Rainfall has a profound effect on the disturbed river ecosystems, rather than pristine or undisturbed rivers; in particular, river biochemical oxygen demand (BOD), turbidity, electrical conductivity, and nitrogen-phosphorus (N-P) nutrients were found to markedly increase following rainfall, due to an influx of nutrients from the surrounding environment [6]. Despite the differences in rainfall characteristics, the biomass of algae (green algae and diatoms) and zooplankton in rivers generally increases after rainfall [7,8]; the fish biomass also typically increases, signifying bottom-up ecosystem characteristics [9,10]. Studies on the response of riverine ecosystems to rainfall have predominantly focused on the rainfall impacts on water quality, fish, invertebrates, and phytoplankton [11–14]; however, studies on the effects of rainfall on epilithic diatom communities are currently limited.

Epilithic diatoms account for 20% of the total global carbon fixation and include the most diverse taxonomic groups of algae [15]. Along with bacteria, they form biofilms on the surface of substrates, such as rocks and pebbles. Diatoms undergo a biofilm cycle in running water by absorbing nutrients, increasing their cell density, and desorbing after reaching a certain growth stage [16,17]. Benthic algae that inhabit running waters, such as streams or rivers, are the main food source for high-level predators, such as aquatic insects and fish [18–20]. To understand climate change-induced changes in river flow and its effects on biotic communities, the long-term monitoring of rainfall patterns during the monsoon season and its impacts on epilithic diatom communities should be investigated.

Our research team previously reported the impacts of monsoon rainfall on the river diatom community [21,22]. To understand the impact or its magnitude of rainfall, we compared physico-chemical and biological parameters before and after the monsoon, and analyzed the relationship between water quality parameters and biological indices (dominance, diversity, eveness and richness).

In this study, for the pursuit of more visible performance on the shift of the diatom community, we also propose and used a community dynamic index of epilithic diatoms (CDI) based on a simple ordination method (i.e. principal component analysis, PCA) of biological data. CDI reflects the magnitude of change between two communities before and after monsoon rainfall. Before the introduction of CDI method, we conducted the pre-test using various ordination methods.

The main aim of this work is to study the impacts of Asian monsoon rainfall patterns on the river environmental characteristics and over the epilithic diatom communities. For that, an investigation of the water characteristics and epilithic diatom communities was conducted for the Hantangang River in the central Korean peninsula before and after the monsoon season in the period of 2012–2015, including 2013, the year of highest rainfall.

2. Materials and Methods

2.1. Study Area

As a study site, the Hantangang River is a major tributary of the Imjin River, with a length of 141.0 km and a drainage area of 2436.4 km^2. The river's source is located in Cheorwon, Gangwon-do and the river converges with the Imjin River in Yangju-gun, Gyeonggi-do, which then flows toward the west coast (Figure 1). The river is a major water resource for various uses. Its main tributaries include Youngpyeongcheon, Pocheoncheon, Sincheon, and Chatancheon [23]. The upstream region consists of canyons and has a high flow velocity, due to its large river regime coefficient and a dominant river bed composition of rocks and pebbles. The region also serves as a leisure-sports venue in summer.

The onset of the summer monsoon in Far East Asia—including South Korea, China, and Japan—is abrupt, as opposed to gradual [24]. The timing of the summer monsoon varies between each country according to their location. In South Korea, the monsoon mainly occurs between June and September and is accompanied by localized heavy rainfall [25]. When the summer rainy season is influenced by the summer monsoon, localized heavy rainfall can occur twice a year [26,27]. For example, localized

heavy rainfall occurred twice in the Hantangang River in 2012; however, the absence of this pattern in other years implies that it is not typical. We observed high precipitation during the study period, with a maximum of 1101.7 mm in 2013 and a minimum of 386.7 mm in 2014 (Figure 2). The rainfall varied significantly within the study period (p < 0.001). The annual mean precipitation of the Gyeonggi-do region—including the Hantangang River—was 1200–1500 mm, and 50%–60% (600–900 mm on average) occurred during the summer rainy season.
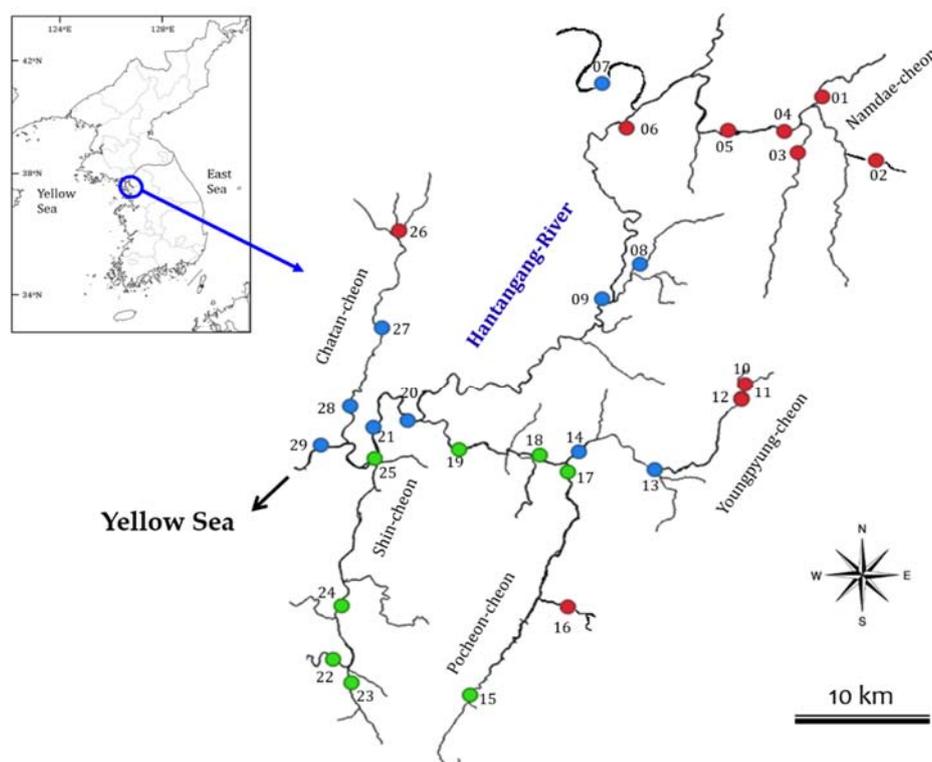
Figure 1. Map of the sampling sites in the Hantangang River in South Korea for epilithic diatom and water analysis. Sampling has been conducted twice a year between 2012 and 2015. Color circles indicate the sampling sites of three groups, such as G1 (red), G2 (blue) and G3 (green). Groups were divided by a cluster analysis (see Results section).

To compare the rainfall between the 1st and 2nd samplings or among survey years, we calculated the total precipitation measured by a weather center of South Korea (http://www.kma.go.kr/index.jsp). The 1st sampling's rainfall before monsoon (PBM) is the sum of all precipitation during the cold and dry season from late autumn to the late spring, while the 2nd rainfall or precipitation after monsoon (PAM) is the sum of all precipitation during the warm season from late spring to the late autumn. In Hantan River Basin, the average rainfall during the monsoon period for 4 years was about 2.5 times higher than that of non-monsoon periods.
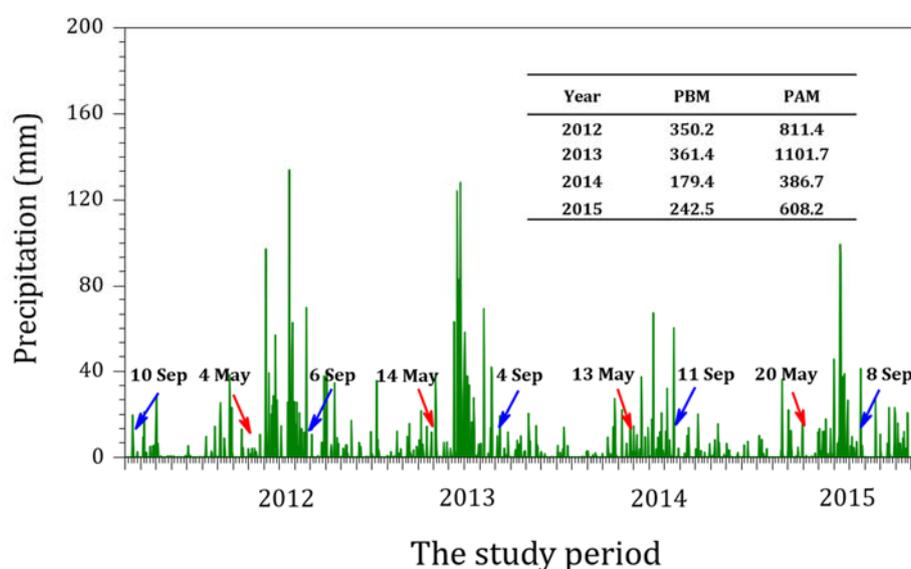
Figure 2. Daily precipitation in the Hantangang River basin between 2012 and 2015, measured by a Korea Weather Center (http://www.kma.go.kr/index.jsp). The arrows are the sampling dates before (red) and after the monsoon (blue), respectively. A small table in the figure showed the total precipitation for the periods of before (PBM) and after monsoon (PAM); In 2012, PBM or the former indicate the sum of daily precipitation from 10 September to 3 May, while PAM or the latter are those from 4 May to 6 September of 2012, respectively.

2.2. Sampling of River Diatom and Waters

To collect epilithic diatoms and river water samples, a total of 29 sites was selected within the mainstream and tributaries of the Hantangang River (Figure 1). Since 2007, the study sites have been continuously monitored for aquatic communities and water quality with land-use under the project of NIER (National Institute of Environmental Research, Korea). Sampling campaigns were conducted twice a year; in May (pre-monsoon) and September (post-monsoon), between 2012 and 2015.

2.3. Analysis of Water Quality Parameters

At each sampling site, the water temperature, dissolved oxygen, pH, electrical conductivity, and turbidity were measured using a portable water quality measuring device (Horiba U-50, HORIBA Ltd., Japan). Water samples were collected using a Van-Dorn type water sampler from the site and transferred to the lab under dark and refrigerated conditions. The samples were then analyzed for BOD, NO_3-N, NH_3-N, TN, PO_4-P, and TP contents. BOD was measured using the Winkler-azide method [28], NO_3-N and TN were measured via cadmium reduction, NH_3-N was measured using the colorimetric method, PO_4-P was measured using the ascorbic acid method, and TP was measured using the ascorbic acid method after persulfate hydrolysis [28]. NO_3-N, NH_3-N, TN, PO_4-P, and TP were analyzed using a spectrophotometer (SP2770i, Youngwoo, Korea).

2.4. Analysis of Epilithic Diatoms

We used a natural rock—with a wide, flat top—as the substrate for collecting epilithic diatoms. When the rain was absent for over two weeks, the rock submerged in water at a depth of 20–30 cm for at least one week was collected. A soft brush was used to collect the diatoms from a 5×5 cm^2 area on the top surface of the rock. After the samples were fixed with Lugol's solution [29], transferred to the laboratory and washed, we produced permanent specimens using the mounting agent Naphrax® (Brunel Microscopes Ltd., England), following the Permanganate method [30].

The total abundance of epilithic diatoms (cell/cm^2) at each study site was quantified using an inverted microscope (Nikon E600, Tokyo, Japan), and the relative abundance (%) of each species was

calculated during the identification process. To calculate the density of diatoms (cells/cm^2), the total abundance of diatoms and the relative abundance of each species were multiplied. These data were used to define the most abundant species, and calculate the dominance [31], diversity [32], richness [33], and evenness [34] of the epilithic diatom communities.

2.5. Measurement of Diatom Community Changes

As mentioned in the introduction, we introduced here a numerical method to measure the shift of diatom community before and after monsoon rainfall. Biotic communities show different characteristics according to abiotic parameters; these characteristics can also significantly change with time [35]. This makes it difficult to determine the degree of the numerical values in response to specific changes, such as a precipitation gradient. In this study, we developed a numerical method for the explanation of community change before and after monsoon rainfall, which is called community dynamic index of epilithic diatom (CDI), based on the principal component analysis. Briefly, as an ordination method for understanding the characteristics of a biological community or ecosystem, many statistical methods, such as principal component analysis (PCA) [36], multidimensional scaling (MDS) [37], principal coordinate analysis (PCoA) [38], extended correspondence analysis (DCA) [39], correspondence analysis (CA) [40], redundancy analysis (RDA) [41] and canonical correspondence analysis (CCA) [42], have often been adopted. Of these, PCA, which uses the Euclidean distance method, minimizes data loss and is easy to visualize or present, even with a small amount of principal component variables [43]. In this study, due to the identification of the changes in biological communities, RDA, DCA, and CCA, which required separate environmental variables, were excluded, while the correction models, such as MDS and PCoA, were not included due to null data. In previous studies, the distance in the PCA dimension before and after monsoon rainfall showed higher eigenvalue (Eigenvalue, 22.498) and variance (11.193) than DCA and CA. These characteristics are also consistent with the study of Ko et al. [43], which was conducted with the data of spider harvested by Ter Braak [42].

The CDI index is easily calculated by the measurement of distance between two points before and after all events or stresses (i.e. natural and artificial), to compare the magnitude or strength of impacts with other sampling sites. The PCA finds the orthogonal axis while maintaining the variance of data to a maximum degree and converts the variables in the higher-dimensional space into a lower-dimensional space with no linear correlation,

The community dynamic index of epilithic diatom (CDI), before and after monsoon rainfall, was calculated by the following equation:

$$ \text{d} \; = \; \sqrt{(x1 - x2)^2 + (y1 - y2)^2} \tag{1} $$

d is the distance between two communities with different times at the specific site in PCA dimension.
x1 and y1 is the first sampling site in PCA dimension before monsoon
x2 and y2 is the second sampling site in PCA dimension after monsoon rainfall

$$ \text{CDI} \; = \; (\sum_{i \, = \, 1}^{n} \text{d}i)/n \tag{2} $$

d*i* is the distance between different times of *i*th community before and after monsoon rainfall
n is the number of sampling sites or communities

2.6. Data Analysis

The abundance of epilithic diatoms were converted to $\log_{10}(x+1)$, to reduce the population variation. As a first step, to understand the characteristics of epilithic diatoms, we performed a cluster analysis (Ward's methods), based on the number and abundance of species of epilithic diatoms

identified from each site. We also conducted an analysis of variance (ANOVA) to compare the differences in biological characteristics (number and abundance of appeared species), community indices (dominant index, diversity, eveness and richness), and water quality between each group. In addition, we applied Pearson's correlation analysis to determine the associations between epilithic diatoms, water quality, and the precipitation during monsoon. In a second step, we performed a principal component analysis (PCA) to calculate the community dynamic index (CDA); the distance between two communities before and after monsoon rainfall. Meanwhile, for the generalization and validation of the CDI to other organisms or communities, we examined the relationship between CDI and the above community indices, using a correlation coefficient analysis. The statistical analyses were performed using PC-ORD (ver. 4.25. MjM Software, Gleneden Beach, OR, USA) and SPSS software (ver. 23. SPSS Inc. Korea).

3. Results

3.1. Epilithic Diatoms of the Hantangang River

Between 2012 and 2015, we identified a total of 201 different taxa of epilithic diatoms, including two orders, three suborders, eight families, 32 genera, 175 species, 15 varieties, two forma, and nine unidentified taxa (not shown).

The results of cluster analysis were based on species or abundance showed the existence of three groups (G1–3) (Figure 3). G1 comprises 11 sampling sites predominantly located in the mainstream of the Hantangang River and the upstream tributaries; G2 comprises 10 sites predominately located in the mid- and downstream sections of the river; and G3 comprises eight sites and includes the Sincheon tributary, which enters the downstream region of the Hantangang River.
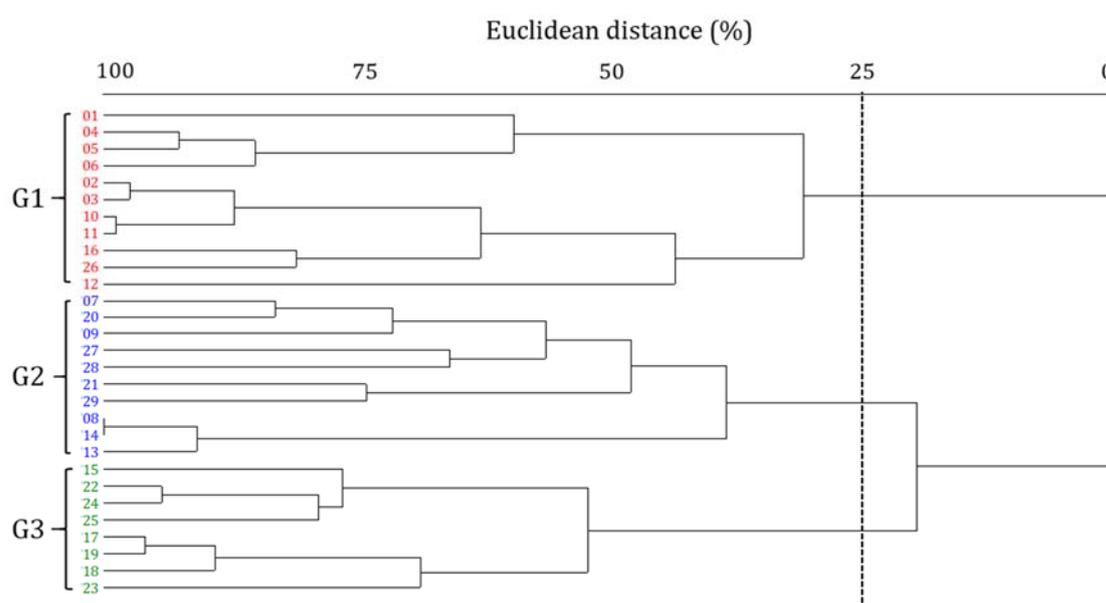
Figure 3. Dendrogram of on the epilithic diatom communities of 29 sampling sites of the Hantangang River, Korea, from 2012–2015.

The community characteristics of the epilithic diatoms in this study are shown in Tables 1 and 2 and Figures 4 and 5. Abundance showed no difference between the groups, whereas the diversity, richness, and number of species were higher in G2. The dominant species in each group were Table 2: in G1, *Achnanthidium alteragracillimum* (26.7%–6.1%) in the pre-monsoon periods, and *Achnanthidium minutissimum* (27.3%–29.8%) dominated in the post-monsoon periods; in G2 and G3, *Nitzschia fonticola* (26.0%–43.2%) dominated in the pre-monsoon periods, and *Nitzschia palea* (14.0%–45.2%) in the post-monsoon periods. Both species showed similar trends in two groups.

Table 1. Physicochemical and biological variables of the epilithic diatom communities (G1–3) in the Hantangang River, from 2012 to 2015.

Variables	G1	G2	G3	F	p
WT	18.8 ± 3.0^a	22.7 ± 3.0^b	24.9 ± 2.8^c	83.457	<0.001
DO	8.7 ± 1.0	9.3 ± 1.5	9.2 ± 2.6	2.829	0.061
pH	7.3 ± 0.5^a	7.9 ± 0.6^c	7.7 ± 0.5^b	26.001	<0.001
EC	97 ± 59^a	171 ± 119^a	728 ± 564^b	89.128	<0.001
Turb	8.5 ± 6.4^a	18.6 ± 9^b	26.7 ± 12.4^c	73.017	<0.001
BOD	0.8 ± 0.4^a	1.7 ± 0.9^a	7.3 ± 5.4^b	103.037	<0.001
NH_3-N	0.21 ± 0.24^a	0.59 ± 0.67^a	2.84 ± 2.78^b	61.559	<0.001
NO_3-N	1.24 ± 0.54^a	1.75 ± 0.64^b	1.84 ± 1.02^b	15.715	<0.001
TN	2.37 ± 0.88^a	3.30 ± 1.23^b	6.28 ± 3.22^c	80.512	<0.001
PO_4-P	0.02 ± 0.02^a	0.07 ± 0.07^b	0.16 ± 0.15^c	41.414	<0.001
TP	0.04 ± 0.04^a	0.11 ± 0.11^b	0.25 ± 0.25^c	41.944	<0.001
Biomass	29.3 ± 32.7	27.2 ± 27.0	31.8 ± 29.4	0.412	0.663
No. species	28.5 ± 7.9^b	37.7 ± 9.2^c	23.2 ± 6.5^a	61.606	<0.001
Dominance (DI)	0.55 ± 0.16^a	0.50 ± 0.16^a	0.63 ± 0.16^b	12.076	<0.001
Diversity (H′)	3.06 ± 0.73^b	3.42 ± 0.79^c	2.64 ± 0.74^a	19.424	<0.001
Richness (j)	2.29 ± 0.70^b	3.06 ± 0.87^c	1.80 ± 0.54^a	55.323	<0.001
Evenness (e)	0.64 ± 0.11^b	0.66 ± 0.12^b	0.59 ± 0.13^a	6.233	0.002

Superscripts a, b, and c are Tukey's post hoc test after the Bonferroni test. WT: water temperature (°C), DO: dissolve oxygen (mg/L), EC: electronic conductivity (μS/Cm) Turb.: Turbidity (NTU), BOD: biochemical oxygen demand (mg/L), TN: total nitrogen (mg/L) TP: total phosphorus (mg/L), NH_3-N, NO_3-N, PO_4-P: mg/L, Biomass (10^4 cells/cm^2).

Table 2. The dominant species and their relative abundances (%) in each diatom community (G1–3), before (1st) and after (2nd) the monsoon in the Hantangang River from 2012 to 2015.

Years		G1	G2	G3
2012	BF	*Achnanthidium alteragracillimum* (36.1)	*Nitzschia fonticola* (43.2)	*Nitzschia palea* (19.1)
	AF	*Achnanthidium convergens* (22.5)	*Nitzschia palea* (14.0)	*Nitzschia palea* (27.6)
2013	BF	*Achnanthidium convergens* (38.5)	*Nitzschia fonticola* (26.0)	*Nitzschia fonticola* (27.6)
	AF	*Achnanthidium convergens* (43.3)	*Achnanthidium minutissimum* (16.1)	*Nitzschia palea* (45.2)
2014	BF	*Achnanthidium convergens* (30.8)	*Nitzschia palea* (54.4)	*Nitzschia palea* (22.4)
	AF	*Achnanthidium minutissimum* (29.8)	*Nitzschia palea* (20.2)	*Nitzschia palea* (26.8)
2015	BF	*Achnanthidium alteragracillimum* (26.7)	*Nitzschia fonticola* (31.2)	*Nitzschia fonticola* (31.5)
	AF	*Achnanthidium minutissimum* (27.3)	*Fragilaria elliptica* (20.0)	*Nitzschia palea* (26.3)

BF: before monsoon, AF: after monsoon.

In addition, the most abundant species in the Hantangang River were *Nitzschia fonticola* (before monsoon, BF: 8.3×10^6 cells/cm^2, after monsoon, AF: 0.7×10^6 cells/cm^2), *Nitzschia palea* (BF: 3.8×10^6 cells/cm^2, AF: 4.9×10^6 cells/cm^2), and *Achnanthidium convergens* (BF: 3.5×10^6 cells/cm^2, AF: 2.6×10^6 cells/cm^2) (Figure 4). *Achnanthidium convergens* and *Achnanthidium alteragracillimum* were most abundant in G1; *Nitzschia fonticola* and *Nitzschia palea* the largest in G2; and *Nitzschia palea*, and *Navicula minima* in G3. The species showing variability in abundance before and after rainfall were *Achnanthidium alteragracillimum* (G1), *Nitzschia fonticola* (G2), and *Nitzschia palea* (G3). The correlation analysis between the dominant species, environmental factors, and the precipitation during monsoon between each group is shown in Table 3. *Ach. convergens* and *Ach. alteragracillimum* of G1 and *Nitzschia fonticola* of G2 were positively correlated with nutrients such as NH_4, NO_3, TN, PO_4 and TP. In contrast, *Nitzschia palea*—the most abundant species of G3—negatively correlated with the same nutrients (Table 3). Water temperature also showed a similar pattern to the nutrients. However, we could not understand the role of temperature on diatom communities during the monsoon.
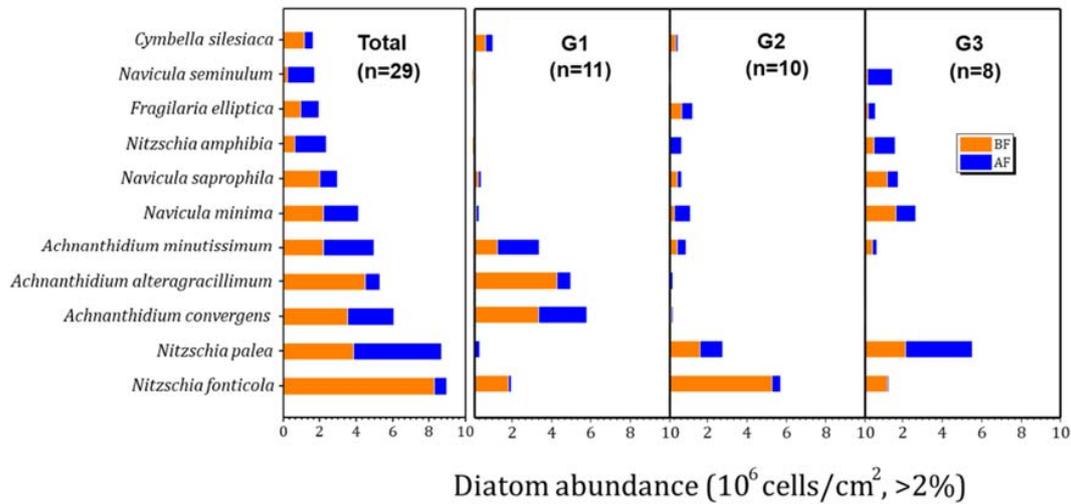
Figure 4. Total abundances of most abundant epilithic diatom species in each group (G1–3) in the Hantangang River before (BF) and after monsoon (AF) from 2012 to 2015. BF: before monsoon, AF: after monsoon.
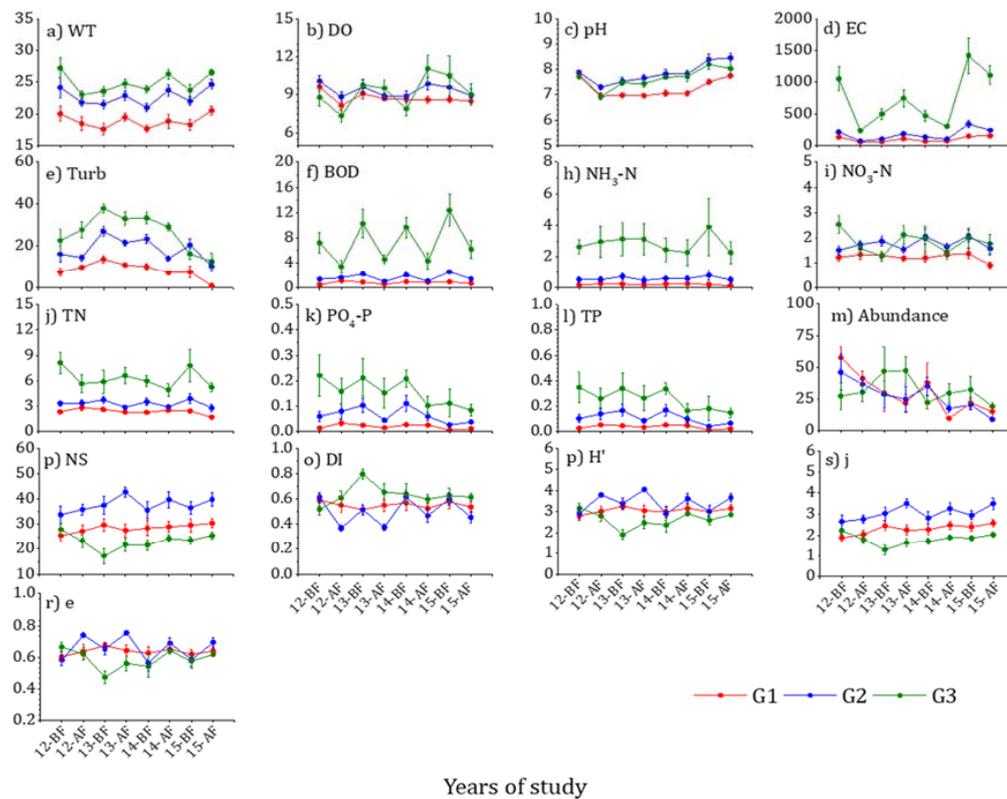
Figure 5. The temporal variability of the biological and physicochemical variables of each group (G1–3) in the Hantangang River, from 2012 to 2015. WT: water temperature (°C), DO: dissolve oxygen (mg/L), EC: electronic conductivity (μS/Cm), Turb: Turbidity (NTU), BOD: biochemical oxygen demand (mg/L), TN: total nitrogen (mg/L), TP: total phosphorus (mg/L), NH_3-N, NO_3-N, PO_4-P: mg/L, NS: number of species, BF: before monsoon, AF: after monsoon. DI; Dominance index, H'; Diversity index, j; Richness index, e; Evenness index, 12-BF and 12-AF: the measurements before and after monsoon in 2012, respectively.

Table 3. The correlation coefficients between the dominant diatom species (DS) and water quality parameters before and after the monsoon in the Hantangang River, from 2012 to 2015.

DS	Rain	WT	DO	pH	EC	Turb.	BOD	NH3-N	NO3-N	TN	PO4-P	TP	Group
ACCN	-	−0.55 **	-	−0.25 **	−0.59 **	−0.37 **	−0.60 **	−0.58 **	−0.36 **	−0.63 **	−0.48 **	−0.48 **	G1
ACAL	-	−0.36 **	-	−0.13 *	−0.41 **	−0.32 **	−0.51 **	−0.55 **	−0.30 **	−0.55 **	−0.44 **	−0.45 **	G1
ACMI	-	−0.34 **	-	−0.24 **	−0.53 **	−0.33 **	−0.49 **	−0.54 **	−0.25 **	−0.55 **	−0.36 **	−0.38 **	G1
NIFO	−0.29 **	−0.22 **	0.15 *	-	−0.16 *	-	−0.21 **	−0.32 **	0.19 **	−0.18 **	−0.19 **	−0.17 **	G2
NIPA	0.23 **	0.49 **	-	0.23 **	0.49 **	0.39 **	0.45 **	0.41 **	0.31 **	0.42 **	0.29 **	0.29 **	G3
NAMI	-	0.23 **	-	-	0.32 **	0.21 **	0.29 **	0.25 **	0.25 **	0.26 **	0.21 **	0.23 **	G3

* $p < 0.05$, ** $p < 0.01$. ACCN: Achnanthidium convergens, ACAL: Achnanthidium alteragracillimum, ACMI: Achnanthidium minutissimum, NIFO: Nitzschia fonticola, NIPA: Nitzschia palea, NAMI: Navicula minima. WT: water temperature (°C), DO: dissolve oxygen (mg/L), EC: electronic conductivity (μS/Cm), Turb.: Turbidity (NTU), BOD: biochemical oxygen demand (mg/L),TN: total nitrogen (mg/L), TP: total phosphorus (mg/L), NH_3-N, NO_3-N, PO_4-P: mg/L.

3.2. Water Quality Parameters of the Hantangang River

The ANOVA results on water quality parameters showed differences among the three groups divided by the cluster analysis based on the distribution of epilithic diatoms (Table 1, Figure 5). Most of the water parameters including electrical conductivity, turbidity, BOD, and nutrients such as NH_4, NO_3, TN, PO_4 and TP, showed the lowest values in G1, indicating the highest water quality among groups. Conversely, G3 showed the opposite trend, with the most turbid water of the three groups. G2 displayed an intermediate trend (Figure 5). G1 maintained the cleanest water quality throughout the entire study period, with small variability before and after monsoon. Although conductivity, BOD, and nitrogenous nutrients were similar between G1 and G2, turbidity and phosphorus nutrients showed obvious differences. Turbidity decreased after rainfall in all investigations, and phosphorus nutrients decreased after rainfall in all investigations, except in 2012. Conductivity and BOD showed the highest variation of all water quality parameters in G3: conductivity increased in 2013 during the highest rainfall of the study period, whereas BOD decreased after rainfall throughout the entire investigation period. Similarly, TP and PO_4-P also decreased after rainfall.

3.3. Shift in Diatom Communities before and after Monsoon

The variation in diatom community, such as number and abundance of species, dominance (DI), species diversity (H'), richness index (j) and evenness index (e) before and after monsoon rainfall, occurred throughout the study period (Figure 5).

The abundance of both G1 and G2 decreased after rainfall, whereas G3 showed no consistent trend. The richness index and number of species were highest in G2 in all investigations and consistently increased after rainfall. In contrast, G1 and G3 were not consistent. Indices of dominance and diversity in G2 and G3 indicated the obvious change of epilithic diatom community before and after monsoon rainfall, such as increases of species diversity, converse to dominant index. T-test results also supported the distinct changes of biological index as dominance and diversity after rainfall (P<0.01 for two, data not shown).

In the PCA ordination, all diatom communities clearly changed before and after monsoon rainfall from 2012–2015, regardless of sampling sites (Figure 6A). The eigenvalues of axis 1 and 2 were 14.1 and 8.4, respectively, and together, they explain 11.2% of the total variance (significance level of $p < 0.001$). In addition, the correlations between axis 1 and 2 with rainfall were −0.23 ($p < 0.01$) and −0.32 ($p < 0.01$). The positive and negative regions on axis 1 in the PCA ordination correspond to the before and after monsoon rainfall data, respectively. Meanwhile, the positive region on axis 2 is divided into the before rainfall G1 and G2 data and the after rainfall G2 and G3 data. The negative region on axis 2 is divided into the after rainfall G1 and before rainfall G2 data. These results of the PCA ordination therefore demonstrate clear differences between groups with different water quality.

The shift in diatom community or community dynamic index of epilithic diatom (CDI) of three groups before and after monsoon rainfall from 2012–2015 (Figure 6B) showed the highest values in G2, the mid-polluted river, indicating a relative higher fluctuation of diatom species, compared to the clean or polluted water. However, the group showed significant differences only in 2013, in response to the highest annual rainfall during the study period ($p < 0.001$).
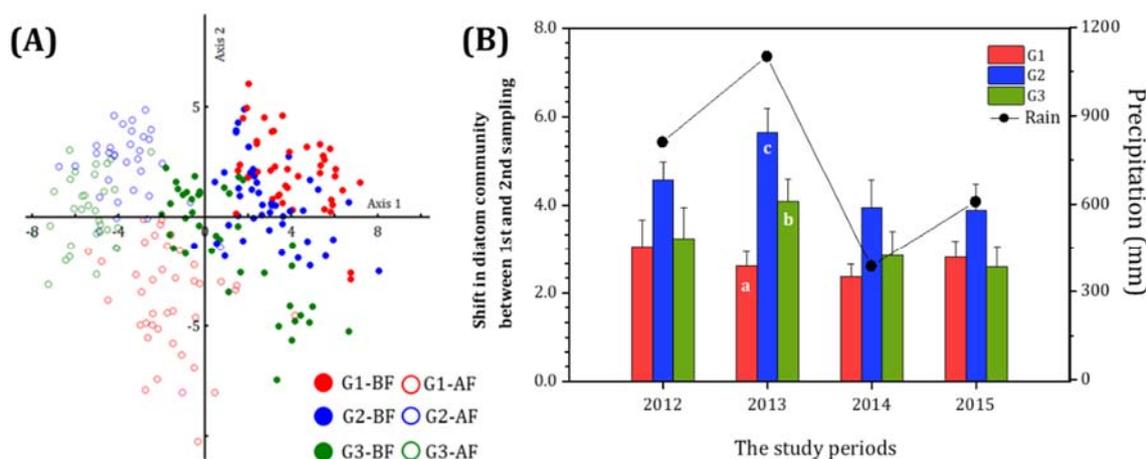
Figure 6. Epilithic diatom community characteristics before and after monsoon in the Hantangang River from 2012 to 2015, including (**A**) the PCA ordination and (**B**) the CDI or average of distances of each group between the before (1-BF) and after monsoon (2-AF) period. Black circle is total annual precipitation during the monsoon period every year. Example, G1-BF and G1-AF: the sampling sites of group 1(G1) before (red-closed circle) and after monsoon (red-open circle), respectively.

There was a significant relationship between CDI and classical biological indices shown throughout all the study sites and periods (Table 4), except for the abundance. The number of species, diversity, richness and evenness indices were significantly correlated with CDI, and the dominant index was negatively correlated with CDI. These results indicate the potential of PCA-base CDI as a measure of community change of the ecosystem. However, this study is limited to a small river, so, more studies are needed to generalize the understanding of the shift of various communities with natural or artificial events.

Table 4. The correlation coefficients between the community dynamic index of epilithic diatom (CDI) and biological indices in the Hantangang River from 2012 to 2015. ** $p < 0.01$.

Biological Indices	CDI
Abundance	−0.03
No. of species	0.44 **
Dominant index	−0.31 **
Diversity index	0.35 **
Richness index	0.41 **
Evenness index	0.28 **

4. Discussion

All water quality parameters (conductivity, turbidity, BOD, NH_3-N, NO_3-N, TN, PO_4-P, and TP) showed higher concentrations in G3, which comprises the tributaries and the downstream region of the main river. Lower values were observed in G1 and G2, which comprises the upper and middle reaches of the main river. This pattern infers a complex downstream gradient [44], which may be caused by a number of factors, such as nutrient concentrations, soil usage, and flow velocity.

Environmental factors are the dominant controls on epilithic diatom communities [44], but spatial factors are also important. In our study, we identified high spatial variability in the epilithic diatom communities, according to stream order. Moreover, the dominant diatom species differed between each group in response to differences in water quality. The dominant species in G1 were *Achnanthidium alteragracillimum* and *Ach. convergens*, which are mainly clean-water species [45,46]. G2 and G3 had a mixed population of clean-water and turbid-water species, with a dominance of *Nit. fonticola*, *Nitzschia palea*, and *Ach. minutissimum* in G2, and a dominance of *Nit. fonticola* and *Nit. palea* in G3 [47–49].

As concluded by other studies around the world [50,51], these results suggest that water quality significantly affects the epilithic diatoms in the Hantangang River.

Rainfall directly influences the physicochemical characteristics of rivers—including nutrient concentrations. For example, increased riverine flood flow was found to be the dominant contributor toward increased suspended solid concentrations in rivers [52]. Moreover, previous studies [6,53,54] have demonstrated a significant increase in water quality indices (BOD, PO_4-P, total suspended particulate matters, surfactants, and turbidity) after rainfall, which contradicts our study results. Ion and nutrient concentrations in rivers are greatly affected by flow rate, and studies have inferred elevated water pollution in response to concentrated rainfall [55–58]. In contrast, we observed improved water quality in the Hantangang River during the post-monsoon periods, in both G2 and G3. The previous studies analyzed water quality immediately after rainfall, whereas water quality was analyzed at least two weeks after rainfall in our study. The contrasting results could therefore be due to differences in the timing of the water quality measurements.

In this study, the cellular abundance of typical of oligotrophic waters diatom species, *Ach. alteragracillimum* and *Nit. fonticola*, decreased after rainfall, despite improved water quality. On the other hand, *Nit. palea* as dominant species in the polluted water increased in abundance after monsoon rainfall (Table 2, Figure 4). This may suggest that the rainfall can strongly influence the most abundant diatom species following the stream condition with different water quality. Other studies showed that diatoms are pioneer species that attach to substrates immediately after the occurrence of floods that wash out most of the substrates. The monsoonal climate of South Korea likely influences the appearance of the common pioneer species *Ach. minutissimum* [59]. Our results are consistent with the study, but do not explain the abrupt decrease of *Ach. altergracillima* after rainfall. In addition, not all pennate diatoms increased after rainfall, and thus, further studies should investigate the introduction of pioneer species on substrates immediately following severe environmental disturbance like rainfall. The community dynamic index of epilithic diatom (CDI), showed a positive or negative significant relation to biological indices. Thus, we believe that the CDI methods would be the simplest tool to numerically measure the shift of various biotic communities in aquatic and terrestrial ecosystems. Although it is difficult to define the threshold or limit of the CDI values due to the various event by response interactions according to the biotic community, they may be useful to compare the relative impact magnitude with another community.

This study also showed that the community change of epilithic diatoms was not consistent with water quality before and after monsoon rainfall. Previously, the polluted sites highly improved water quality after rainfall, while the biotic community or CDI of the mid-polluted water became worse. It may suggest that communities that are in a better condition, with a higher diversity of species, are better able to cope with extreme disturbances such as that caused by monsoons, while impoverished communities are less resistant or resilient to those changes, as suggested by Feio et al. [60] Poorer communities are less affected because they are already composed only of very resistant taxa.

5. Conclusions

We examined the influence of rainfall before and after monsoon rainfall on epilithic diatom communities and water quality parameters at the Hantangang River, South Korea, from 2012–2015. Water quality in the polluted sites had improved following rainfall, but the abundance of dominant species was not directly associated to their sensitivity; *Nitzschia fonticola* decreased in all sampling sites, and *Nitzschia palea* in the clean sites and *Achnanthidium minutissimum* in the polluted sites increased after rainfall, respectively. Based on the principal component analysis (PCA), the community dynamic index of epilithic diatom (CDI) indicates that the shift of diatom community in the mid-polluted sites in 2013—the year of highest rainfall, was the most obvious among groups. These study results indicate that the monsoon rainfall strongly influences water quality and diatom communities. Thus, further studies are needed to generalize the effects of monsoon rainfall on water quality and epilithic diatom

communities, which should include more rivers with different environmental characteristics, and data on rainfalls with different magnitudes, and exposure periods.

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