The spatial pattern of periphytic algae communities and its corresponding mechanism to environmental variables in the Weihe River Basin, China

Yixin Liu, Jiaxu Fu, Dandong Cheng, Qidong Lin, Ping Su, Xinxin Wang and Haotian Sun

ABSTRACT

Periphytic algae is a useful indicator of aquatic ecological conditions. We investigated the periphytic algae on natural substrate and the environmental variables at 44 sites on three river systems in the Weihe River Basin (WRB). A total of 84 species are identified, representing 37 genera. The most common genera were *Navicula, Oscillatoria, Nitzschia*, *Scenedesmus*, *Cymbell,* and *Fragilaria.* One-way analysis of variance (ANOVA) indicated significant differences among the three river systems in environmental variables ($p < 0.05$). Non-metric multidimensional scaling (NMDS) analyses also showed differences in periphytic algae communities in the three river systems ($p < 0.05$) and identified different dominant species in each river system. Canonical correspondence analysis (CCA) and Monte Carlo permutation tests revealed that nutrient concentration, WT, and altitude were the most important variables affecting the structure and distribution of periphytic algae communities. Chemical variables were the most accounted for environmental variables (12.5%), while physical variable and geographical factors (5.8% in total) play a relevant minor role. Our results demonstrate that *Navicula pupula, Navicula radiosq, Nitzschia palea,* and *Nitzschia denticula*, exhibiting wide ecological amplitude, are tolerant of high concentrations of nutrient pollution. Variation of periphytic algae communities in WRB is due to the combination of anthropogenic and natural factors including agricultural and domestic wastes water inputting, land use patterns, geology, climatic changes, and river hydrology.

Key words | CCA, environmental variables, nutrients, periphytic algae, Weihe River Basin

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HIGHLIGHTS

- Structure and distribution of periphytic algae communities were investigated in the Weihe River Basin.
- The gradient of organic pollution detected in environmental variables was the main gradient, and the periphytic algae responded to this gradient.
- The types of substrates in river impact periphytic algae abundance, causing higher periphytic algae abundance in cobbles substrate.
- The variation of periphytic algae communities is attributed to the combination of anthropogenic factors and natural factors.
- The results support the periphytic algae as ecological indicators in the Weihe River Basin.

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INTRODUCTION

Periphytic algae are found in bodies of water ranging from small ponds to the global ocean. They are a major contributor to primary productivity in the river, playing a vital role in aquatic ecosystems (Kolmakov *et al.* 2008; Pandey *et al.* 2017). Periphytic algae have been widely associated with different geographical regions with specific environmental conditions (Soininen 2002; Kovács *et al.* 2006; Chen *et al.* 2016a). Composition and relative abundance of the periphytic algae community vary with their ecological affinity and preferences (Potapova & Charles 2003; Tornés *et al.* 2007). Their structure and distribution are reflected in spatially and temporally based geomorphological conditions, climate, hydrology, and water physicochemical properties (Pan *et al.* 2004; Bere *et al.* 2016). Based on observations in the natural river and experiments, studies have shown that the algae will not be nutrient-limited when the nutrients concentration is $P > 30\,\mu g/L$ and $N > 1\,mg/L$ in the river ecosystem (Westlake 1981). Water temperature affects algal photosynthetic metabolism through its control of enzyme reaction rates (Stevenson *et al.* 1996). Periphytic algae abundance reaches a peak at a certain level with suitable bed light levels (Yang & Flower 2012). Hydrodynamic conditions also influence periphytic algae biomass, and the suitable velocity and river depth are 0.9–1.1 m/s and 0.40–0.48 m, respectively (Wang *et al.* 2018a). Periphytic algae are effective environmental indicators due to their wide distribution range, numerous species, and sensitivity to environmental changes (Stevenson *et al.* 2008). They respond rapidly to changes in environmental variables, reflecting the overall ecological quality and the effects of different stressors (Bona *et al.* 2007; Vasiljević *et al.* 2017). Individual algae species often show a clear preference for specific substrates and habitats (Winter & Duthie 2000). Substantial differences exist in species composition and abundance of periphytic algae communities from the same sites but different substrates such as sand, rock surface, submerged, or emergent macrophytes (Fisher & Dunbar 2007; Bere & Tundisi 2011). Therefore, understanding the relationship between environmental factors and the distribution of periphytic algae communities is important for developing algae-based water quality indices.

With the reform and opening-up policy in the 1980s, China began a period of rapid urbanization. The proportion of the urban population increased from 17.9% in 1978 to 52.6% in 2012, while urban built-up areas increased by 78.5% (Bai *et al.* 2014). At the same time, rapid urbanization has brought a series of complex water environmental problems. It greatly affects the hydrological system by channel morphology, water quality, and aquatic biota (White & Greer 2006). The Weihe River Basin (WRB) is the main grain-producing area, and is an important industrial and commercial center in northwest China. The Weihe River is a major source of domestic water, industrial water, and irrigation in the central plain. There are 76 major cities with a total population of 22 million in the basin (Chang *et al.* 2015). Due to the increase in population, industry, and farmland area, the WRB also faces serious water environmental problems. Presently, most studies have focused on the water quality and quantity of the WRB (Jiake *et al.* 2011; Wei *et al.* 2012; Song *et al.* 2015). Research on the effects of urbanization on the aquatic biota in WRB has typically focused on fish communities and macroinvertebrates (Wu *et al.* 2014; Su *et al.* 2019), with few studies available on algae communities. Studies on periphytic algae communities and their relationship with environmental variables have scarcely been carried out in the WRB.

This study focuses on the abundance, species structure, and distribution of periphytic algae communities in the WRB. The specific objectives are to investigate the relationships between periphytic algae communities and environmental variables, to detect which ecological factors explain most of the variation. Our results may provide a valuable baseline for future water quality assessments in the WRB in China.

MATERIALS AND METHODS

Study area

The study was carried out in the WRB (Figure 1), which is located in the northwest of China. The WRB (east longitude 103°5′–110°40′, north latitude 33°40′–37°25′) has a drainage area of $1.35 \times 10^5\,km^2$, with annual mean temperatures

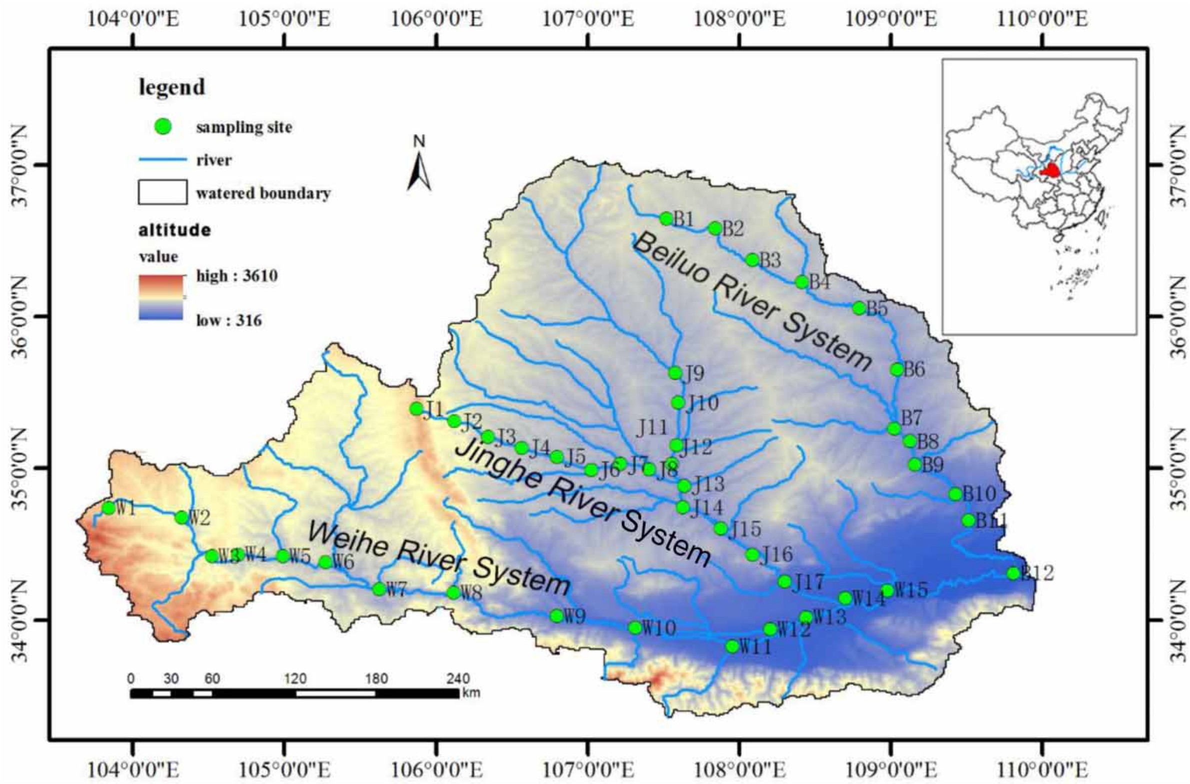

Figure 1 | The locations of the sampling sites in the Weihe River Basin.

between 7.8 and 13.5 °C and the annual mean rainfall ranging from 558 to 750 mm which increases from north to south (Wang *et al.* 2018b). The climate in the WRB is characterized by the temperate continental monsoon. Therefore, precipitation and runoff exhibited strong inter-annual variations and similar intra-annual variations. The runoff from July to October is approximately 65% of the mean annual runoff (Chang *et al.* 2015). Also, most of the WRB is covered by highly erodible loess and soil erosion is serious because of sparse vegetation, uneven rainfall distribution, and high intensity of heavy rain (Song *et al.* 2010). There are three different water systems in the WRB, including the Weihe River System (WRS), the Jinghe River System (JRS), the BeiluoRiver System (BRS), and their tributaries, as well as other small independent streams (Figure 1).

Sampling and analysis

Periphyton samples were collected from 44 sites in the three water systems of WBR in June 2017, each of the water systems has a different number of sampling sites: 15 in WRS (W1–W15), 17 in JRS (J1–J17) and 12 in BRS (B1–B12) (Figure 1). For the cobble-type sedimentary rivers, within the range of 100 m upstream and downstream of the sampling point, nine stones were selected (surface area of the stones <200 cm^2), and scraped with a toothbrush to a 7.07 cm^2 area (Kelly *et al.* 1998). For the silt-type sedimentary rivers, the surface layer of silt on the sampled stones were scraped with an area of 63.62 cm^2 using an inverted Petri dish along the riverbed (Carpenter & Waite 2000). The samples were preserved with 4% formaldehyde and 2% Lugol's iodine solution. An aliquot of the periphytic algae suspension was cleaned by using hydrochloric acid and hydrogen peroxide. The acid-cleaned samples were mounted on microscope slides applying the high refraction mountant Naphrax. Species were identified and a minimum of 400 valves were counted per slide at 1,000× magnification using a microscope (Olympus BX51, Olympus, Tokyo, Japan). Algal cells identification was carried out according to the standard guides of Krammer & Lange-Bertalot

(1986, 1988, 1991a, 1991b), Zhu & Chen (2000), and Hu & Wei (2006). The relative abundance of each observed taxa was calculated.

Basic physical and chemical water parameters were measured directly at the sampling sites during sampling. The water temperature (WT), pH, dissolved oxygen (DO), electrical conductivity (EC), and total dissolved solids (TDS) were measured *in situ* using a portable water quality meter (HACH HQ40d). River velocity was acquired by using a portable flow meter (MGG/KL-DCB); river width data was obtained with the help of Trupulse 200; river depth was measured by using a terrain probe; Secchi depth (SD) was measured using a Secchi disc, except for some of the restored rivers that were transparent to the bottom; latitude longitude and altitude (Altit) information was obtained with a Global Positioning System (GPS Etrex 201X). Two parallel water samples were collected with a water sampler and poured into a 1,000 mL bottle at each sampling point. The water sample was fixed with acid, stored in a 4 °C incubator and transported back to the laboratory to measure the concentrations of nitrate (NO_3-N, mg·L^{-1}), ammonium (NH_4-N, mg·L^{-1}), total nitrogen (TN, mg L^{-1}), total phosphorus (TP, mg·L^{-1}) following the Chinese Government standard for Water and Wastewater Monitoring and Analysis (2002). Major ions (K^+, Mg^{2+}, Cl^-) were measured using the Dionex Ion Chromatography System (ICS; ICS-1000, Dionex, Sunnyvale, CA, USA).

Data analysis

The counts of each algae taxon were expressed as relative abundance before the analysis. The structural properties of the periphytic algae community at each site were used to characterize by the Shannon–Weiner index (H′) and species richness (S) (Bellinger *et al.* 2006; Wang *et al.* 2017). These indicators are commonly used in the biological assessment of water quality (Spellerberg & Fedor 2003). Non-metric multidimensional scaling (NMDS) analyses were performed to visualize the periphytic algae structure distribution characteristics of the WRB. Furthermore, the analysis of similarity (ANOSIM, Bray-Curtis distance measure, 999 permutations) was used to test the difference in the community structure. Both NMDS and ANOSIM analyses were performed using PRIMER version 5 (Clarke & Warwick 2001).

A total of 18 rivers geographical, hydrological, physical and chemical variables were considered for data analysis, including Altit, WT, width, depth, SD, velocity, flux, pH, DO, EC, TDS, NO_3-N, NH_4-N, K^+, Mg^{2+}, Cl^-, TN and TP. All of the environmental variables, except pH, were transformed as log10 $(x+1)$ before analysis. One-way analysis of variance (ANOVA) was used to evaluate the significance of the differences among the WRS, the JRS and the BRS sites based on the physical and chemical variables of the transformed water, completed by IBM SPSS Statistics for Windows (25). Principal component analysis (PCA) was applied to explore the main environmental gradients among the sampling sites, using CANOCO 5.0 (Ter Braak & Smilauer 2012).

Multivariate analyses are mathematical tools that detect the relationship between periphytic algae and environmental variables, indicating the main variables and revealing the similarities among algae samples. For analysis of their relation, 28 species were retained with rare species (<1%) removed. The removal of the species with a relative abundance of less than 1% can minimize the influence of rare species in the analysis. Algae abundance data were transported by log10 $(x+1)$ to stabilize variances and give more weight to the larger species often found at low relative abundance in periphytic algae communities, which are important for defining assemblage (Tison *et al.* 2005). Detrended correspondence analysis (DCA) was conducted to detect the gradient length of the algae abundance data. Gradient lengths were then used to select the appropriate model (linear or unimodal model) for the constrained ordinations. In this study, the longest gradient of four ordination axes was 3.8, indicating that a linear or unimodal model could be applied to the ordination analysis (Ter Braak & Verdonschot 1995). Hence, the unimodal ordination technique of canonical correspondence analysis (CCA) was used to assess the relationships between environmental variables and periphytic algae communities from different sites. A Monte Carlo permutation test (999 permutations, $p \leq 0.05$) was used to reduce the environmental variables to those correlating significantly with the first two CCA axes. Both DCA and CCA were performed using CANOCO 5.0 (Ter Braak & Smilauer 2012).

RESULTS

Environmental gradients

In this study, considerable fluctuations were identified in hydrological characteristics, water physical and chemical properties among sampling sites (Table 1). One-way ANOVA indicated that among all the environmental variables, width, pH, TDS, NO_3-N, Mg^{2+}, and Cl^- were significantly different, $p < 0.05$ (Table 1). The average width and the concentration of NO_3-N in the BRS sites were lower than those in the WRS and the JRS ($p < 0.05$), while the concentrations of TDS and Cl^- in the BRS sites were higher than other sites ($p < 0.05$). The average pH and the concentration of Mg^{2+} in the BRS sites was higher than in WRS and JRS ($p < 0.001$). Principal component analysis (PCA) accounted for 63.17% of the total variability in the environmental data in the first two axes (Figure 2). The first axis of PCA explained 41.73% of the variance, indicating that variables were primarily related to Cl^-, K^+, and TDS (Figure 2). The second axis explained 21.44% of the variance, mainly correlating with pH, flux, and river width (Figure 2).

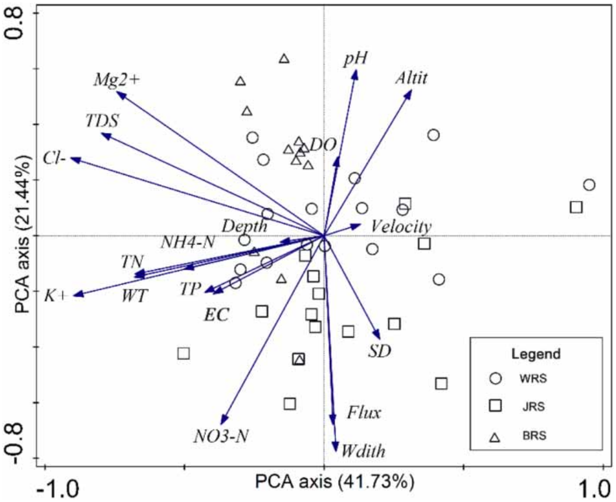

Figure 2 | Analysis of the principal components (PCA) of sampling sites based on environmental variables. WRS, JRS, and BRS are indicated by different symbols.

Table 1 | Mean value (range in parentheses) from three water system sites in July 2017

Environment variables	Abbreviation	WRS $n = 15$	JRS $n = 17$	BRS $n = 12$	P
Altitude (m)	Altit	913 (340–2,452)	1,049 (410–1,950)	821 (340–1,360)	0.162
Water temperature (°C)	WT	22 (6.5–28.5)	21.5 (9.0–25.5)	26 (20.3–29.5)	0.088
River width (m)	Width	73.99 (12.3–210)	40.21 (16.9–105)	33.13 (2.5–133)	0.033*
River depth (m)	Depth	0.47 (0.2–1)	0.47 (0.25–0.65)	0.42 (0.25–0.5)	0.671
Water velocity (m/s)	Velocity	0.54 (0.29–1.02)	0.55 (0.1–1.29)	0.52 (0.07–1.27)	0.901
Flux (m^3/s)	Flux	16.53 (2.87–70.40)	8.71 (1.93–19.53)	6.11 (0.47–16.46)	0.088
Secchi depth (m)	SD	0.16 (0.07–0.52)	0.10 (0–0.35)	0.08 (0–0.3)	0.134
Dissolved oxygen (mg/L)	DO	8.45 (5.55–10.03)	8.69 (7.24–11.92)	9.36 (3.98–13.93)	0.79
pH	pH	9.00 (8.16–9.59)	9.31 (8.01–10.05)	9.63 (9.05–10.14)	0.001**
Electrical conductivity (μs/cm)	EC	837.07 (391–1,618)	789.02 (132.4–1,893)	1,274.33 (336–2,155)	0.075
Total dissolved solids (mg/L)	TDS	372.75 (125–845)	682.45 (89.6–2,115)	893.17 (312–1,944)	0.003*
Total nitrogen (mg/L)	TN	5.55 (1.09–8.21)	4.81 (1.84–9.76)	5.86 (2.78–10.05)	0.423
Total phosphorus (mg/L)	TP	0.11 (0.03–0.25)	0.20 (0.03–1.95)	0.13 (0.02–0.47)	0.808
Nitrate (mg/L)	NO_3-N	2.31 (0.19–4.19)	1.21 (0.04–2.50)	1.65 (0.47–3.59)	0.018*
Ammonium (mg/L)	NH_4-N	0.34 (0.09–0.63)	0.31 (0.10–0.82)	0.29 (0.01–0.74)	0.687
Potassium (mg/L)	K^+	5.07 (0.49–14.68)	5.12 (0.50–11.87)	5.21 (3.82–7.25)	0.683
Magnesium (mg/L)	Mg^{2+}	21.28 (7.64–59.54)	52.05 (4.87–131.69)	70.40 (20.6–135.72)	0.000**
Chloride (mg/L)	Cl^-	145.36 (1.02–380.23)	265.71 (0.84–824.23)	486.26 (160.89–960.55)	0.008*

The value of *n* is the number of water samples in the sites. Variables significantly different among the river systems with $p < 0.05$ and $p < 0.001$ are marked (based on the ANOVA).
*$p < 0.05$; **$p < 0.001$.

Spatial distribution of periphytic algae community structure

A total of 84 periphytic algae taxa species were identified, distributing in 37 genera. Only 28 species and 14 genera were found to reach a relative abundance of more than 1% (Figure 3). The most common genera were *Navicula* (46.5% of all counted), Oscillatoria (5.8%), *Nitzschia* (4.8%), *Scenedesmus* (4.0%), *Cymbell* (3.6%), *Fragilaria* (3.3%), *Diatoma* (3.2%), *Phormidium* (3.1%), *Synedra* (2.8%), *Cyclotella* (2.0%), *Srauroneis* (1.9%), *Cocooneis* (1.3%), *Achnanthes* (1.2%) and *Melosira* (1.0%). These 14 genera accounted for 84.5% of all the values counted (Figure 3). The dominant genus of each site differed in relative abundance. In the WRS sites, *Navicula*, *Fragilaria*, *Scenedesmus*, and *Melosira* occupied a higher relative abundance (20% in at least one sample). *Navicula radiosq*, *Navicula palcentula*, *Fragilaria intermedia*, *Scenedesmus acutiformis* and *Melosira granulata* were the most dominant species (a relative abundance of 10% in at least one sample). In the JRS sites, *Navicula*, *Cymbella*, *Diatoma*, *Oscillatoria* and *Phormidium* occupied a higher relative abundance. The most abundant species were *Cymbella ventricosa*, *Diatoma vulgare*, *Oscillatoria tenuis* and *Phormidium tenue*. In the BRS sites, *Navicula*, *Scenedesmus* and *Oscillatori* were dominant species, but the most abundant species different from WRS and JRS were *Navicula gracilis*, *Navicula pupula* and *Scenedesmus quadricauda*.

In the analyzed set of samples, the density of periphytic algae ranged from 525 to 5.9×10^5 ind/cm^2, species richness from 2 to 29, and the Shannon–Weiner index from 0.58 to 4.43 (Figure 4). The periphytic algae density showed a low level in the whole WRB. The average of periphytic algae density was 7.35×10^4 ind/cm^2 while the highest density and the lowest density appeared at sites J1 and J11, respectively (Figure 4(a)). The average species richness of the periphytic algae communities in WRS, JRS, and BRS were 13, 11, and 14, respectively, with sites J2 and J9 displaying the highest and lowest species richness (Figure 4(b)). The average Shannon–Weiner indexes in WRS, JRS, and BRS were 2.90, 2.45, and 2.99, respectively. The peak and valley values of the Shannon–Weiner index appeared at sites J2 and J15 (Figure 4(c)). According to the results of NMDS and ANOSIM ($r = 0.291$, $p = 0.001$), the periphytic algae community structures were significantly different among WRS, JRS, and BRS (Figure 5).

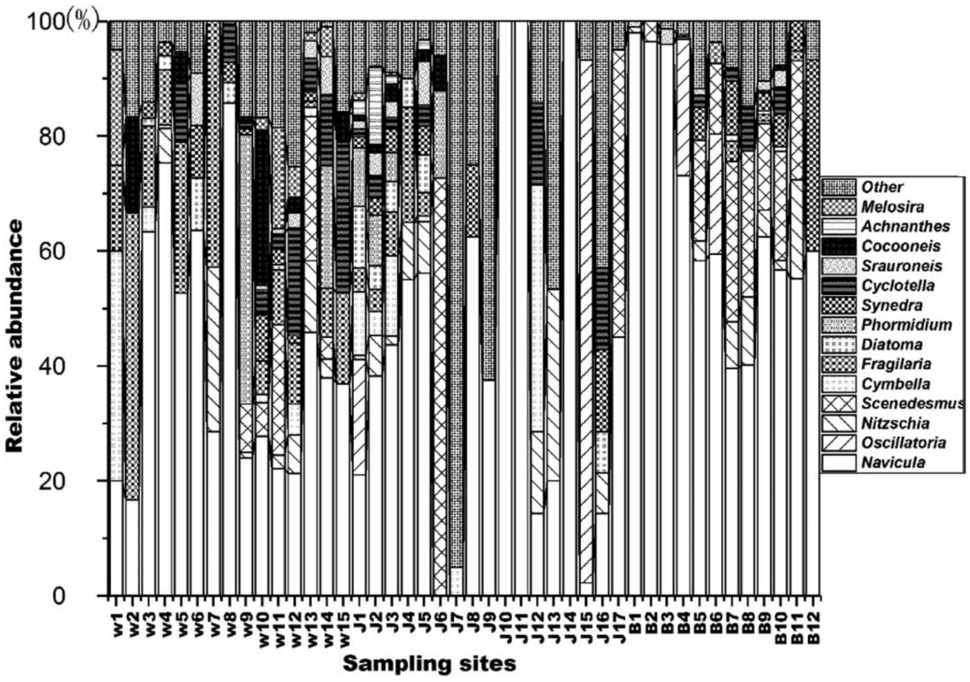

Figure 3 | Percentage composition of 14 genera (relative abundance of each genus >1%) at the sampling sites.

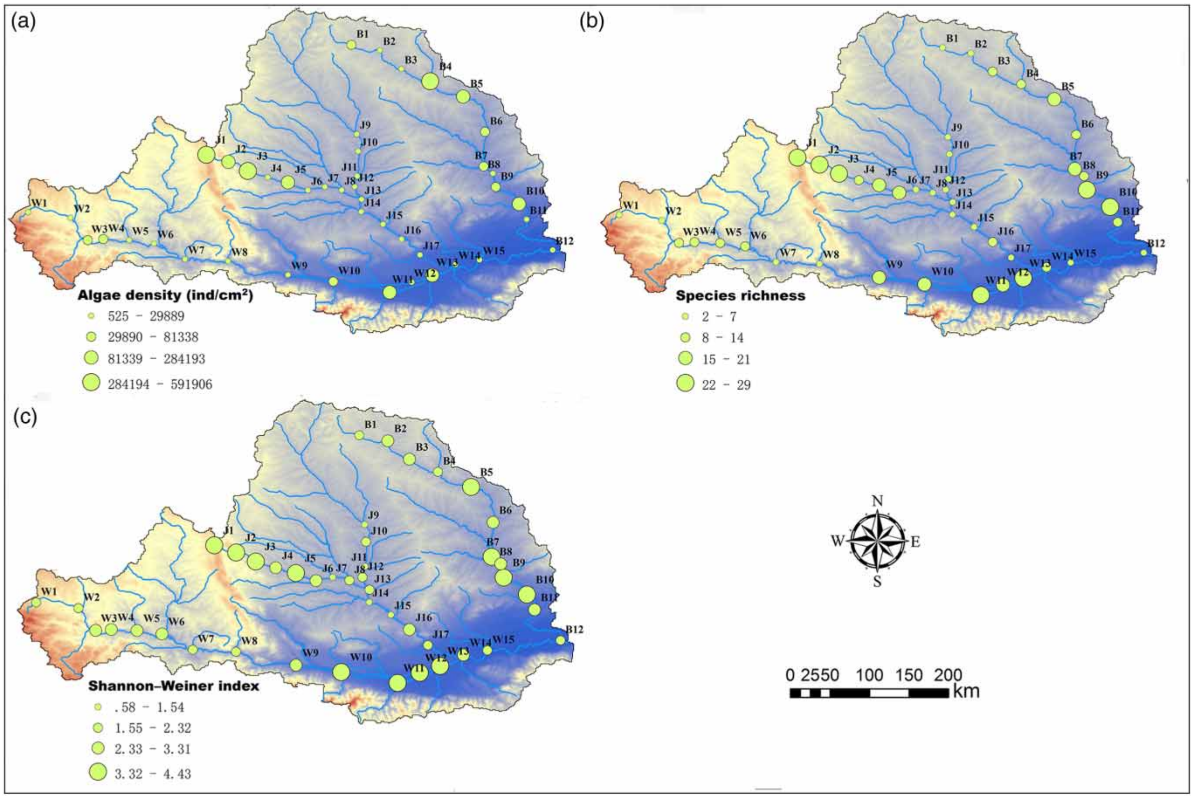

Figure 4 | Structure and distribution of periphytic algae community in the Weihe River Basin: (a) algae density, (b) species richness, (c) Shannon–Weiner index.

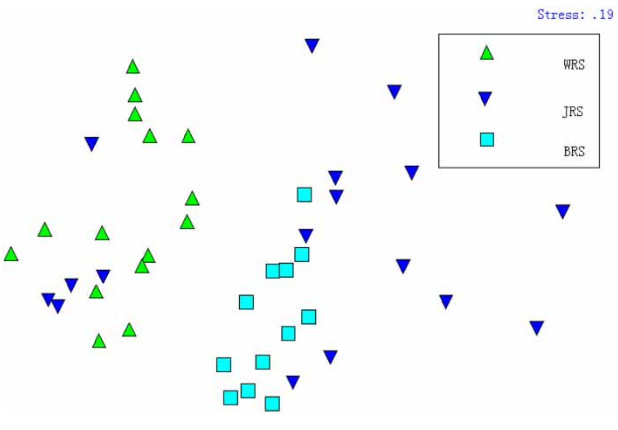

Figure 5 | Nonparametric multidimensional scaling (NMDS) ordination of sampling sites.

Relationship between periphytic algae communities and environment variables

CCA analyzed 28 species and 18 environmental variables at 44 sites (Supplementary material, Table A.1). The Monte Carlo unrestricted permutation test ($p < 0.05$) identified eight environmental variables (Altit, WT, TDS, EC, K^+, Mg^{2+}, Cl^-, TN) that significantly contributed to the algae species assemblages (Figure 6). The eigenvalues of the first two CCA axes ($\lambda_1 = 0.316$, $\lambda_2 = 0.133$) explained 49.1 and 20.7% of the variation in species and environmental variables, respectively (Table 2). The species-environment correlations were high for both of the ordination axes ($r_1 = 0.833$, $r_2 = 0.842$). Axis 1 was positively correlated with TDS ($r = 0.74$), EC ($r = 0.48$), WT ($r = 0.41$), TN ($r = 0.35$), K^+ ($r = 0.41$), Mg^{2+} ($r = 0.73$), Cl^- ($r = 0.69$) and negatively with Altit ($r = -0.23$). Axis 2 was positively correlated with Altit ($r = 0.61$) and negatively with EC ($r = 0.49$) and WT ($r = -0.4$).

The environmental variables play important roles in the distribution of periphytic algae communities. Frequently found species such as *Cocconeis placentula*, *Navicula radiosq*, *Navicula pupula*, *Stauroneis ancepse*, *Nitzschia denticule*, *Nitzschia palea* and *Synedra acus* exhibited wide tolerance to environmental variables (Figure 6(a)). These species were positively associated with Altit, WT, EC, and TN. Most sites in WRS and JRS were distributed in the second and the third quadrant, where the samples

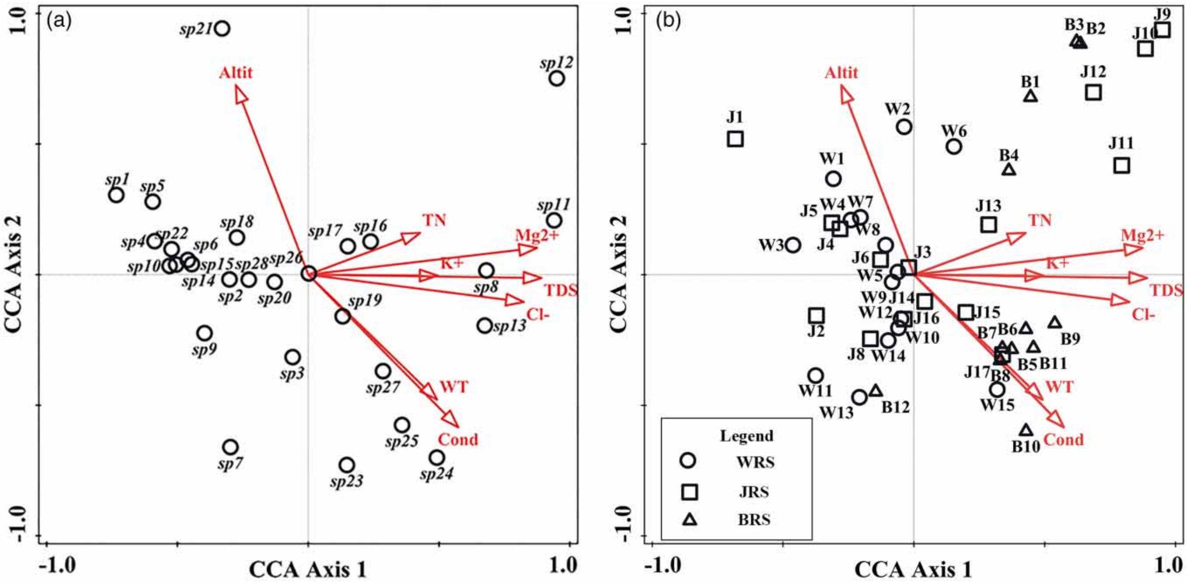

Figure 6 | Canonical correspondence analysis (CCA) showed the relationship of periphytic algae species (a) and sampling sites (b) with significant environmental variables. Legend: sp1: *Achnanthes dispar*, sp2: *Cocconeis placentula*, sp3: *Cyclotella meneghiniana*, sp4: *Cymbella ventricosa*, sp5: *Diatoma vulgare*, sp6: *Fragilaria intermedia*, sp7: *Melosira granulate*, sp8: *Navicula cari*, sp9: *Navicula cari var.angusta*, sp10: *Navicula dicephala*, sp11: *Navicula exigua*, sp12: *Navicula gracilis*, sp13: *Navicula graciloides*, sp14: *Navicula minuscula*, sp15: *Navicula palcentula*, sp16: *Navicula pupula*, sp17: *Navicula radiosq*, sp18: *Navicula simplex*, sp19: *Nitzschia denticule*, sp20: *Nitzschia palea*, sp21: *Oscillatoria tenuis*, sp22: *Phormidium tenue*, sp23: *Scenedesmus acutiformis*, sp24: *Scenedesmus bijugayus*, sp25: *Scenedesmus quadricauda*, sp26: *Stauroneis anceps*, sp27: *Synedra acus*, sp28: *Synedra ulna*.

Table 2 | Summary of the CCA of most dominant periphytic algae species composition in 44 samples concerning the eight environmental variables

Axes	**1**	**2**	**3**	**4**
Eigenvalues	0.316	0.133	0.055	0.045
Species-environment correlations	0.833	0.842	0.725	0.665
Cumulative percentage variance of species data	15.9	22.7	25.4	27.7
Species–environment relation	49.1	69.8	78.3	85.3

were closely related to Altit (Figure 6(b)). The parameter was highly positively associated with *Navicula simplex*, *Scenedesmus acutiformis*, *Scenedesmus bijugayus* and *Scenedesmus quadricauda*. However, the sites in the BRS were mainly dispersed in the fourth quadrant. Samples were associated with high WT and EC (Figure 6(b)).

DISCUSSION

Rivers, an important part of the ecosystem, not only have ecological functions but also provide various services for people. However, river ecosystems are increasingly impacted by environmental stressors, owing to urbanization and industrialization taking place in the entire watershed, contributing to nutrients and organic pollution continuously (Song *et al.* 2015). Wastewater from industrial and agricultural activities, as well as an urban settlement, is the main source that contributes a great number of solid organic pollution and thermal pollution (Milovanovic 2007; Luo *et al.* 2009; N'guessan *et al.* 2009). Algae are an essential component in maintaining the health of aquatic ecosystems (Kelly *et al.* 1998). In general, periphytic algae are regarded as a good indicator of water quality. Many studies have demonstrated that the composition and structure of the periphytic algae community are affected by various environmental variables (Chessman *et al.* 1999; Soininen *et al.* 2004; Urrea & Sabater 2009; Panahy Mirzahasanlou *et al.* 2019).

In this study, we compared the species composition and distribution of periphytic algae communities among three river systems. Though each river system was represented and dominated by different periphytic algae taxa, we found that the genera *Navicula* existed at all samples and species *N. radiosq*, *N. pupula* and *N. simplex* were found in almost every site. From the whole WRB, the species diversity and abundance of periphytic algae changed significantly. Meanwhile, we found that algae abundance was higher at the sites of JRS (J1–J5), part sites of WRS (W11, W13) and BRS (B4, B5, B10), where the forest coverage is high and the substrate of the river is dominated by boulders and cobbles (Supplementary material, Table A.2). The impact of habitat quality on the periphytic algae communities is more significant, especially the type of substrate (Eloranta & Andersson 1998; Bere & Tundisi 2011). Soil and water loss in the WRB is serious, and a large amount of sediment is dumped into the main river, causing soft-sediment substrate at many sites. Periphytic algae abundance in the soft-sediment substrate is lower than the stone substrate (Townsend & Gell 2005).

Periphytic algae communities were associated with three sets of environmental variables in the WRB. One set is a geographic variable, and only one variable is Altit. The other two sets are physical and chemical variables of the WRB. The physical variable is mainly WT. Chemical variables consist of TDS, TN, and nutrient ion concentration. For the geographical and physical variables, the WT changed significantly due to the large east–west span of the WRB and drastic variation in altitude. The similarity of periphytic algae community is related to the altitude distance, and the altitude gradient affects the biodiversity by affecting the local environmental factors (Teittinen *et al.* 2016). Chemical variables are significantly correlated with periphytic algae data indicating that they are a key factor for the distribution of periphytic algae communities (Potapova & Charles 2002; Soininen *et al.* 2004; Tan *et al.* 2014).

The three sets of environmental variables provided information on how they affected the periphytic algae community structure (Leira & Sabater 2005; Blettler *et al.* 2019). The CCA indicated that the chemical variables (12.5%) were the most accounted for in the contribution to the periphytic algae community structure in the WRB, while physical variables and geographical factors (5.8% in total) played a relevant minor role. The periphytic algae composition in the river system downstream sites was greatly influenced by high EC, Mg^{2+}, Cl^- and TN concentration. The high concentration of these variables may be due to the domestic sewage and industrial wastewater draining to the river (Ma *et al.* 2009). The other main reason is due to soil erosion which not only carries sediment into the river, increasing water turbidity, but also dissolves soluble nutrients and ions in the soil, increasing the concentration of various particles, pollutants and ions (Quilbé *et al.* 2006). EC is an index that can reflect the total ionic concentration in natural water. In this research, EC became an important determinant to distinguish the distribution of the periphytic algae communities in the WRB. We found that the average values of EC concentration in downstream sites was 1,110 μm/cm, higher than 759 μm/cm measured in upstream sites. TDS and nutrient levels play an important role in benthic periphytic algae community structure. Most of the abundant and common species were characteristic of eutrophic ecosystems (Van Dam *et al.* 1994). In the WRB, high TN concentration from anthropogenic sources are likely to cause genera *Naviacula* (46.5%) and *Nitzschia* (4.8%), which have wide ecological amplitude and pollution tolerance, dominating in samples (Goma *et al.* 2005; Delgado & Pardo 2015; Chen *et al.* 2019).

WT can affect the concentration of dissolved oxygen in water and the respiratory rate of aquatic organisms, so it also is a major factor affecting the periphytic algae community (Chen *et al.* 2016b). Moreover, because that altitude drastically drops from upstream to downstream in the WRB, WT also changes evidently and becomes a significant factor affecting the periphytic algae. Thermal pollution is equally a reason for WT rising. Thermal energy absorbed and stored by urban impervious underlying surface and rainwater runoff and point discharge from wastewater treatment plants increase WT (Van Buren *et al.* 2000; Kinouchi *et al.* 2007).

Recently, the impact of catchment-scale variables on river ecosystems has attracted researchers' attention. A widely used approach is to establish relationships between community patterns and environmental variables (Liu *et al.* 2016). In this study, Altit, WT and nutrition concentration were retained in the CCA as significantly affecting algal distribution environmental factors. The impact of increased nutritional levels caused by human activities is significantly greater than natural factors. Our work has important implications for river biomonitoring and management in the study area, especially in other subtropical regions throughout China.

CONCLUSIONS

There are complex variables which affect the structure and distribution of periphytic algae communities, including hydrological, geographical and physiochemical factors. Our results revealed that altitude, EC, TN, WT and major ions were identified as the main variables with a significant influence on the structure and distribution of periphytic algae communities. Three river systems were investigated, each of them with different dominant species, and corresponding to the different variables. Multivariate analyses are a good tool for interpreting species data but a large part of variation remained unexplained in most instances. This uncertainty may be related to other variables which can explain why variation and species have broad tolerance to the variables (Passy 2007; Centis *et al.* 2010; Porter-Goff *et al.* 2013; Tolkkinen *et al.* 2016). Consequently, the main determinants of variation of periphytic algae communities may result from a combination of the change in land-use patterns by man, natural phenomena including geology and climatic changes and river hydrology.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Bai, X. M., Shi, P. J. & Liu, Y. S. 2014 Realizing China's urban dream. *Nature* **509** (7499), 158–160.

Bellinger, B. J., Cocquyt, C. & O'Reilly, C. M. 2006 Benthic diatoms as indicators of eutrophication in tropical streams. *Hydrobiologia* **573**, 75–87.

Bere, T. & Tundisi, J. G. 2011 The effects of substrate type on diatom-based multivariate water quality assessment in a tropical river (Monjolinho), São Carlos, SP, Brazil. *Water Air Soil Pollut.* **216** (1–4), 391–409.

Bere, T., Mangadze, T. & Mwedzi, T. 2016 Variation partitioning of diatom species data matrices: understanding the influence of multiple factors on benthic diatom communities in tropical streams. *Sci. Total Environ.* **566**, 1604–1613.

Blettler, M. C., Oberholster, P. J., Madlala, T., Eberle, E. G., Amsler, M. L., De Klerk, A. R., Truter, J. C., Marchese, M. R., Latosinski, F. G. & Szupiany, R. 2019 Habitat characteristics, hydrology and anthropogenic pollution as important factors for distribution of biota in the middle Paraná River, Argentina. *Ecohydrol. Hydrobiol.* **19** (2), 296–306.

Bona, F., Falasco, E., Fassina, S., Griselli, B. & Badino, G. 2007 Characterization of diatom assemblages in mid-altitude streams of NW Italy. *Hydrobiologia* **583**, 265–274.

Carpenter, K. D. & Waite, I. R. 2000 Relations of habitat-specific algal assemblages to land use and water chemistry in the Willamette Basin, Oregon. *Environ. Monit. Assess.* **64** (1), 247–257.

Centis, B., Tolotti, M. & Salmaso, N. 2010 Structure of the diatom community of the River Adige (North-Eastern Italy) along a hydrological gradient. *Hydrobiologia* **639** (1), 37–42.

Chang, J., Wang, Y., Istanbulluoglu, E., Bai, T., Huang, Q., Yang, D. & Huang, S. 2015 Impact of climate change and human activities on runoff in the Weihe River Basin, China. *Quat. Int.* **380**, 169–179.

Chen, X., Bu, Z., Stevenson, M. A., Cao, Y., Zeng, L. & Qin, B. 2016a Variations in diatom communities at genus and species levels in peatlands (central China) linked to microhabitats and environmental factors. *Sci. Total Environ.* **568**, 137–146.

Chen, X., Zhou, W., Pickett, S. T., Li, W., Han, L. & Ren, Y. 2016b Diatoms are better indicators of urban stream conditions: a case study in Beijing, China. *Ecol. Indic.* **60**, 265–274.

Chen, S., Zhang, W., Zhang, J., Jeppesen, E., Liu, Z., Kociolek, J. P., Xu, X. & Wang, L. 2019 Local habitat heterogeneity determines the differences in benthic diatom metacommunities between different urban river types. *Sci. Total Environ.* **669** (1), 711–720.

Chessman, B., Growns, I., Currey, J. & Plunkett-Cole, N. 1999 Predicting diatom communities at the genus level for the rapid biological assessment of rivers. *Freshwater Biol.* **41** (2), 317–331.

Clarke, K. R. & Warwick, R. M. 2001 Changes in marine communities: an approach to statistical analysis and interpretation. *Mt. Sinai J. Med.* **40** (5), 689–692.

Delgado, C. & Pardo, I. 2015 Comparison of benthic diatoms from Mediterranean and Atlantic Spanish streams: community changes in relation to environmental factors. *Aquat. Bot.* **120**, 304–314.

Eloranta, P. & Andersson, K. 1998 Diatom indices in water quality monitoring of some South-Finnish rivers. *SIL Proc. 1922–2010* **26**, 1213–1215.

Fisher, J. & Dunbar, M. 2007 Towards a representative periphytic diatom sample. *Hydrol. Earth Syst. Sci. Discuss.* **11** (1), 399–407.

Goma, J., Rimet, F., Cambra, J., Hoffmann, L. & Ector, L. 2005 Diatom communities and water quality assessment in

Mountain Rivers of the upper Segre basin (La Cerdanya, Oriental Pyrenees). *Hydrobiologia* **551**, 209–225.

Hu, H. J. & Wei, Y. X. 2006 *The Freshwater Algae of China: Systematics, Taxonomy and Ecology*. Science Press, Beijing, China.

Jiake, L., Huaien, L., Bing, S. & Yajiao, L. 2011 Effect of non-point source pollution on water quality of the Weihe River. *Int. J. Sediment Res.* **26** (1), 50–61.

Kelly, M., Cazaubon, A., Coring, E., Dell'Uomo, A., Ector, L., Goldsmith, B., Guasch, H., Hürlimann, J., Jarlman, A. & Kawecka, B. 1998 Recommendations for the routine sampling of diatoms for water quality assessments in Europe. *J. Appl. Phycol.* **10** (2), 215–224.

Kinouchi, T., Yagi, H. & Miyamoto, M. 2007 Increase in stream temperature related to anthropogenic heat input from urban wastewater. *J. Hydrol.* **335** (1–2), 78–88.

Kolmakov, V., Anishchenko, O., Ivanova, E., Gladyshev, M. & Sushchik, N. 2008 Estimation of periphytic microalgae gross primary production with DCMU-fluorescence method in Yenisei River (Siberia, Russia). *J. Appl. Phycol.* **20** (3), 289–297.

Kovács, C., Kahlert, M. & Padisák, J. 2006 Benthic diatom communities along pH and TP gradients in Hungarian and Swedish streams. *J. Appl. Phycol.* **18** (2), 105–117.

Krammer, K. & Lange-Bertalot, H. 1986 *Bacillariophyceae 1 Teil: Naviculaceae. Süsswasserflora von Mitteleuropa*. Gustav Fischer Verlag, Jena.

Krammer, K. & Lange-Bertalot, H. 1988 *Bacillariophyceae 2. Teil: Bacillariaceae, Epthemiaceae, Surirellaceae. Süsswasserflora von Mitteleuropa*. Gustav Fischer Verlag, Stuttgart.

Krammer, K. & Lange-Bertalot, H. 1991a *Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. Süsswasserflora von Mitteleuropa*. Gustav Fischer Verlag, Stuttgart.

Krammer, K. & Lange-Bertalot, H. 1991b *Bacillariophyceae 4. Teil: Achnanthaceae, Kritische Erg?nzungen zu Navicula (Lineolatae) und Gomphonema. Süsswasserflora von Mitteleuropa*. Gustav Fischer Verlag, Stuttgart.

Leira, M. & Sabater, S. 2005 Diatom assemblages distribution in Catalan rivers, NE Spain, in relation to chemical and physiographical factors. *Water Res.* **39** (1), 73–82.

Liu, S., Xie, G., Wang, L., Cottenie, K., Liu, D. & Wang, B. 2016 Different roles of environmental variables and spatial factors in structuring stream benthic diatom and macroinvertebrate in Yangtze River Delta, China. *Ecol Indic* **61**, 602–611.

Luo, H. B., Luo, L., Huang, G., Liu, P., Li, J. X., Hu, S., Wang, F. X., Xu, R. & Huang, X. X. 2009 Total pollution effect of urban surface runoff. *J. Environ. Sci.* **21** (9), 1186–1193.

Ma, J., Ding, Z., Wei, G., Zhao, H. & Huang, T. 2009 Sources of water pollution and evolution of water quality in the Wuwei basin of Shiyang river, Northwest China. *J. Environ. Manage.* **90** (2), 1168–1177.

Milovanovic, M. 2007 Water quality assessment and determination of pollution sources along the Axios/Vardar River, Southeastern Europe. *Desalination* **213** (1–3), 159–173.

N'guessan, Y. M., Probst, J.-L., Bur, T. & Probst, A. 2009 Trace elements in stream bed sediments from agricultural catchments (Gascogne region, SW France): where do they come from? *Sci. Total Environ.* **407** (8), 2939–2952.

Pan, Y., Herlihy, A., Kaufmann, P., Wigington, J., Van Sickle, J. & Moser, T. 2004 Linkages among land-use, water quality, physical habitat conditions and lotic diatom assemblages: a multi-spatial scale assessment. *Hydrobiologia* **515** (1–3), 59–73.

Panahy Mirzahasanlou, J., Ramezanpour, Z., Nejadsattari, T., Imanpour Namin, J. & Asri, Y. 2019 Temporal and spatial distribution of diatom assemblages and their relationship with environmental factors in Balikhli River (NW Iran). *Int. J. Ecohydrol. Hydrobiol.* **20** (1), 102–111.

Pandey, L. K., Bergey, E. A., Lyu, J., Park, J., Choi, S., Lee, H., Depuydt, S., Oh, Y.-T., Lee, S.-M. & Han, T. 2017 The use of diatoms in ecotoxicology and bioassessment: insights, advances and challenges. *Water Res.* **118**, 39–58.

Passy, S. I. 2007 Diatom ecological guilds display distinct and predictable behavior along nutrient and disturbance gradients in running waters. *Aquat. Bot.* **86** (2), 171–178.

Porter-Goff, E. R., Frost, P. C. & Xenopoulos, M. A. 2013 Changes in riverine benthic diatom community structure along a chloride gradient. *Ecol. Indic.* **32**, 97–106.

Potapova, M. G. & Charles, D. F. 2002 Benthic diatoms in USA rivers: distributions along spatial and environmental gradients. *J. Biogeogr.* **29** (2), 167–187.

Potapova, M. & Charles, D. F. 2003 Distribution of benthic diatoms in US rivers in relation to conductivity and ionic composition. *Freshwater Biol.* **48** (8), 1311–1328.

Quilbé, R., Rousseau, A. N., Duchemin, M., Poulin, A., Gangbazo, G. & Villeneuve, J.-P. 2006 Selecting a calculation method to estimate sediment and nutrient loads in streams: application to the Beaurivage River (Québec, Canada). *J. Hydrol.* **326** (1–4), 295–310.

Soininen, J. 2002 Responses of epilithic diatom communities to environmental gradients in some Finnish rivers. *Int. Rev. Hydrobiol.* **87** (1), 11–24.

Soininen, J., Paavola, R. & Muotka, T. 2004 Benthic diatom communities in boreal streams: community structure in relation to environmental and spatial gradients. *Ecography* **27** (3), 330–342.

Song, J., Xu, Z., Hui, Y., Li, H. & Li, Q. 2010 Instream flow requirements for sediment transport in the lower Weihe River. *Hydrol. Processes* **24** (24), 3547–3557.

Song, J., Yang, X., Zhang, J., Long, Y., Zhang, Y. & Zhang, T. 2015 Assessing the variability of heavy metal concentrations in liquid-solid two-phase and related environmental risks in the Weihe river of shaanxi province, China. *Int. J. Environ. Res. Public Health* **12** (7), 8243–8262.

Spellerberg, I. F. & Fedor, P. J. 2003 A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the 'Shannon–Wiener'Index. *Global Ecol. Biogeogr.* **12** (3), 177–179.

Stevenson, R. J., Bothwell, M. L., Lowe, R. L. & Thorp, J. H. 1996 *Algal Ecology: Freshwater Benthic Ecosystem*. Academic Press, USA.

Stevenson, R. J., Pan, Y., Manoylov, K. M., Parker, C. A., Larsen, D. P. & Herlihy, A. T. 2008 Development of diatom indicators of ecological conditions for streams of the western US. *J. N. Am. Benthol. Soc.* **27** (4), 1000–1016.

Su, P., Wang, X., Lin, Q., Peng, J., Song, J., Fu, J., Wang, S., Cheng, D., Bai, H. & Li, Q. 2019 Variability in macroinvertebrate community structure and its response to ecological factors of the Weihe River Basin, China. *Ecol. Eng.* **140**, 105595.

Tan, X., Ma, P., Xia, X. & Zhang, Q. 2014 Spatial pattern of benthic diatoms and water quality assessment using diatom indices in a subtropical river, China. *Clean Soil Air Water* **42** (1), 20–28.

Teittinen, A., Kallajoki, L., Meier, S., Stigzelius, T. & Soininen, J. 2016 The roles of elevation and local environmental factors as drivers of diatom diversity in subarctic streams. *Freshwater Biol.* **61** (9), 1509–1521.

Ter Braak, C. J. & Šmilauer, P. 2012 *Canoco Reference Manual and User's Guide: Software for Ordination, Version 5.0*. Microcomputer Power Press, Ithaca, USA.

Ter Braak, C. J. & Verdonschot, P. F. 1995 Canonical correspondence analysis and related multivariate methods in aquatic ecology. *Aquat. Sci.* **57**, 255–289.

Tison, J., Park, Y.-S., Coste, M., Wasson, J., Ector, L., Rimet, F. & Delmas, F. 2005 Typology of diatom communities and the influence of hydro-ecoregions: a study on the French hydrosystem scale. *Water Res.* **39** (14), 3177–3188.

Tolkkinen, M., Mykrä, H., Virtanen, R., Tolkkinen, M., Kauppila, T., Paasivirta, L. & Muotka, T. 2016 Land use impacts on stream community composition and concordance along a natural stress gradient. *Ecol. Indic.* **62**, 14–21.

Tornés, E., Cambra, J., Gomà, J., Leira, M., Ortiz, R. & Sabater, S. 2007 Indicator taxa of benthic diatom communities: a case study in Mediterranean streams. *Int. J. Limnol.* **43** (1), 1–11.

Townsend, S. A. & Gell, P. A. 2005 The role of substrate type on benthic diatom assemblages in the Daly and Roper Rivers of the Australian wet/dry tropics. *Hydrobiologia* **548**, 101–115.

Urrea, G. & Sabater, S. 2009 Epilithic diatom assemblages and their relationship to environmental characteristics in an agricultural watershed (Guadiana River, SW Spain). *Ecol. Indic.* **9** (4), 693–703.

Van Buren, M., Watt, W. E., Marsalek, J. & Anderson, B. 2000 Thermal enhancement of stormwater runoff by paved surfaces. *Water Res.* **34** (4), 1359–1371.

Van Dam, H., Mertens, A. & Sinkeldam, J. 1994 A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherland J. Aquat. Ecol.* **28** (1), 117–133.

Vasiljević, B., Simić, S. B., Paunović, M., Zuliani, T., Krizmanić, J., Marković, V. & Tomović, J. 2017 Contribution to the improvement of diatom-based assessments of the ecological status of large rivers – the Sava River case study. *Sci. Total Environ.* **605**, 874–883.

Wang, J., Meier, S., Soininen, J., Casamayor, E., Pan, F., Tang, X., Yang, X., Zhang, Y., Wu, Q., Zhou, J. & Shen, J. 2017 Regional and global elevational patterns of microbial species richness and evenness. *Ecography* **40** (3), 393–402.

Wang, H., Li, Y., Li, J., An, R., Zhang, L. & Chen, M. 2018a Influences of hydrodynamic conditions on the biomass of benthic diatoms in a natural stream. *Ecol. Indic.* **92**, 51–60.

Wang, W., Song, J., Zhang, G., Liu, Q., Guo, W., Tang, B., Cheng, D. & Zhang, Y. 2018b The influence of hyporheic upwelling fluxes on inorganic nitrogen concentrations in the pore water of the Weihe River. *Ecol. Eng.* **112**, 105–115.

Wei, F. 2002 *Water and Waste Water Monitoring and Analysis Methods*, 4th edn. Water and Waste Water Monitoring and Analysis Method Committee, China Environmental Science Press, Beijing (in Chinese).

Wei, S., Yang, H., Song, J., Abbaspour, K. C. & Xu, Z. 2012 System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China. *Eur. J. Oper. Res.* **221** (1), 248–262.

Westlake 1981 *Temporal Changes in Aquatic Macrophytes and Their Environment*. Dynamique de Populations et Qualite de l'Eau, pp. 109–138.

White, M. D. & Greer, K. A. 2006 The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California. *Landsc. Urban Plan.* **74** (2), 125–138.

Winter, J. G. & Duthie, H. C. 2000 Stream epilithic, epipelic and epiphytic diatoms: habitat fidelity and use in biomonitoring. *Aquat. Ecol.* **34** (4), 345–353.

Wu, W., Xu, Z., Yin, X. & Zuo, D. 2014 Assessment of ecosystem health based on fish assemblages in the Wei River basin, China. *Environ. Monit. Assess.* **186** (6), 3701–3716.

Yang, H. & Flower, R. J. 2012 Effects of light and substrate on the benthic diatoms in an oligotrophic lake: a comparison between natural and artificial substrates. *J. Phycol.* **48** (5), 1166–1177.

Zhu, H. Z. & Chen, J. Y. 2000 *Bacillariophyta of the Xizang Plateau*. Science Press, Beijing, China.

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