Aquat Ecol (2007) 41:169–181
DOI 10.1007/s10452-006-9073-z

ORIGINAL PAPER

Epiphytic diatoms associated with a submerged macrophyte, *Vallisneria aethiopica*, in the shallow marginal areas of Sanyati Basin (Lake Kariba): a preliminary assessment of their use as biomonitoring tools

C. Phiri · J. Day · M. Chimbari · E. Dhlomo

Received: 1 April 2006 / Accepted: 26 November 2006 / Published online: 6 January 2007

Abstract Diatom assemblages attached to the leaves of the submerged macrophyte *Vallisneria aethiopica* in the shallow waters of the Sanyati Basin in Lake Kariba were analysed to assess their response to human impact. Human activities occurring within approximately 500 m of the shoreline were assessed at ten sampling sites along the shores of the basin. Eleven human activity factors were assessed and scored on a scale of 0 (not occurring at the site), 1 (low), 2 (medium) and 3 (high). Based on these 11 factors, we obtained a total score for the sites, which were then categorized as either having no human disturbance (0), low human disturbance (1–11), medium human disturbance (12–22) or high levels of human disturbance (23–33). Three sites were categorized as having no human disturbance, one had low disturbance and six had medium level human disturbance. A total of 9993 diatoms belonging to 40 genera were identified. The most abundant genera were *Achnanthidium* and *Gomphonema*, which made up 23.4 and 42.9% of the total diatom count, respectively. *Achnanthidium* dominated in remote areas with minimal human activities, while *Gomphonema* was more abundant in areas adjacent to increased human activities. The relative abundances of *Achnanthidium*, *Denticula*, *Pinnularia*, *Rhopalodia* and *Stauroneis* were negatively and significantly correlated, while that of *Gomphonema* was positively and significantly correlated to the human disturbance score (Spearman correlation, $P < 0.05$). Although the number of genera, the Shannon Diversity Index and evenness did not differ significantly among sites (ANOVA, $P > 0.05$), the lowest levels of these descriptors of community assemblage occurred at sites located near areas with relatively high human activities. The abundances of *Achnanthes*, *Cymbella*, *Denticula*, *Encyonema* and *Pinnularia*, *Bacillaria* and *Mastogloia*, *Diatoma* and *Navicula* and *Eunotia* and *Mastogloia* significantly decreased with increasing levels of total phosphorous, nitrate–nitrogen (N), ammonium–N and water turbidity, respectively (Spearman correlation, $P < 0.05$). Of the16 diatom index of biotic integrity (DIBI) metrics, 11 were significantly correlated with at least one of the environmental variables, while nine metrics were significantly correlated with the composite DIBI. Among the environmental variables the disturbance score was the only one that was significantly correlated with the DIBI. We conclude that although there is need for further work,

---

C. Phiri (✉) · M. Chimbari · E. Dhlomo
University Lake Kariba Research Station,
P.O. Box 48, Kariba, Zimbabwe
e-mail: crispenphiri@yahoo.co.uk

J. Day
Freshwater Research Unit, Department of Zoology,
University of Cape Town, Private Bag,
Rondebosch 7700, South Africa

periphytic diatoms associated with *V. aethiopica* may potentially be useful in assessing ecological conditions or the impact of human activities within the shallow marginal waters of Lake Kariba.

Keywords Biomonitoring · Diatoms · Disturbance · Sanyati Basin · Submerged macrophyte

Introduction

Widespread anthropogenic pressures on aquatic ecosystems caused by rapid urbanization, industrial expansion and agricultural activities have resulted in increased loads of inorganic and organic materials and, consequently, adverse effects on aquatic environments. Water quality assessment is principally a biological problem in that its primary effect is on living organisms (Gaufin 1973). The quality of water is generally reflected in the indigenous communities of aquatic organisms in terms of the composition and diversity of the species present, their population densities and their physiological condition(Weber 1973). Although over the last few decades a number of biological monitoring methods have been developed for the assessment of the condition of freshwater environments, these have rarely been applied in Africa. In the few African countries where regular monitoring of the quality of the aquatic environment is practiced, the tendency has been to concentrate on physical and chemical water quality determinants.

Diatoms (Class Bacillariophyceae) are abundant in almost all aquatic habitats, constituting an estimated 25% of the Earth's primary production (Werner 1977). They are increasingly being used to assess water quality as they are generally species-rich, relatively easy to sample, have quick responses to changes in physical and chemical characteristics and are sensitive to subtle changes in environmental conditions or disturbances that may affect other communities only at greater levels of disturbance (e.g., Dixit et al. 1992; Bahls 1993; Lowe and Pan 1996; Stevenson and Bahls 1999). A number of studies have shown that diatoms are excellent biological indicators for many types of pollution in aquatic systems (Patrick and Palavage 1994; Kelly et al. 1995). However, the use of diatoms in water quality programs in African countries has been limited largely due to a dearth of basic phycological research.

Lake Kariba is a large, minimally polluted and oligotrophic man-made lake, although some areas presently are becoming polluted by increased human activities along its shores. The objective of this study was to determine the response of the periphytic diatom community associated with *Vallisneria aethiopica*, which was the most common and dominant submerged macrophyte during the study period, to human activities or impacts along the shores. It is part of a more comprehensive study aimed at developing a suite of biotic indicators for the assessment of ecological integrity in the shallow zones of Lake Kariba using diatoms and macroinvertebrates.

Materials and methods

Lake Kariba was formed in 1958 by the damming of the Zambezi River. The Zambezi River, with a catchment area of about 1,193,500 km^2, is southern Africa's largest river and is composed of three ecologically distinct zones, the Upper (1078 km), Middle (853 km) and Lower Zambezi (563 km). Lake Kariba lies within the Middle Zambezi zone, between latitudes 16°28′ S and 18°06′ S, and longitudes 26°40′ E and 29°03′ E. The lake has a surface area of 4364 km^2 at the normal operation level of 484 m a.s.I, a length of 276 km, an average width of 19 km and an average depth of 29 m. The lake is shared between Zambia and Zimbabwe and has over the years developed a variety of other uses, such as tourism, aquaculture and inshore and pelagic fishery industries.

The study was carried out in the Sanyati Basin of Lake Kariba (Fig. 1), the easternmost of the five major basins forming the lake. For the purposes of the study, the shoreline was divided into areas with minimal human activities, peri-urban areas and urban areas. The areas of minimal disturbance are located in the southern part of the basin adjacent to Matusadona National Park. Ten sites were selected from these areas in a targeted manner to cover the full range

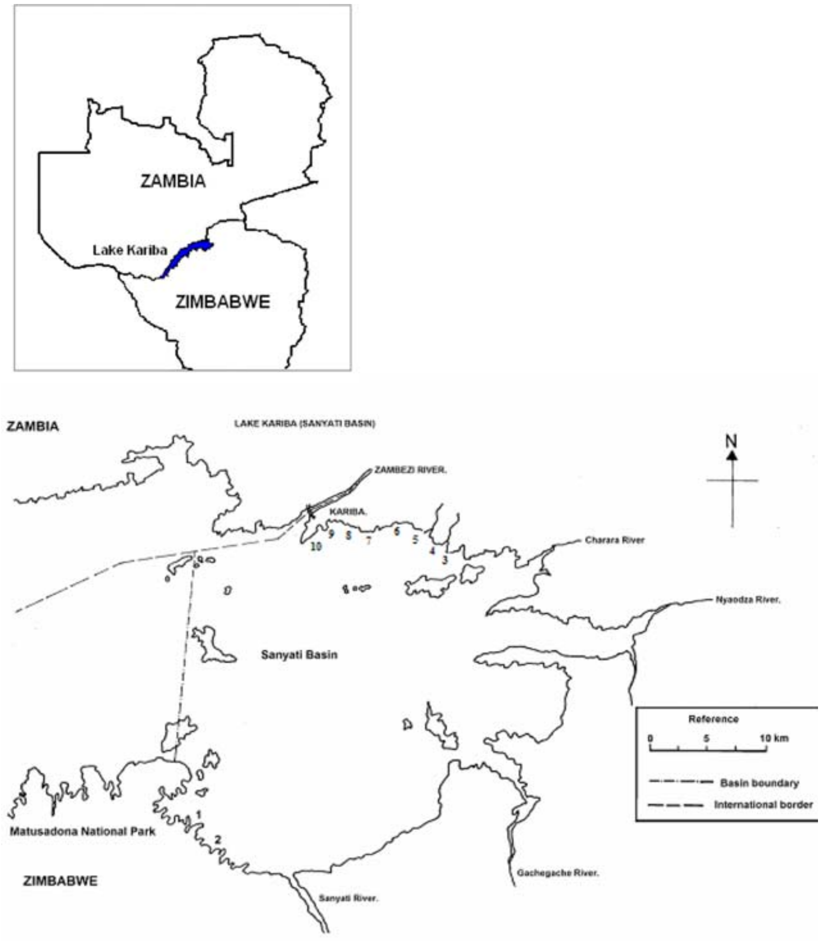

Fig. 1 The location of sampling sites (*1–10*) along the shoreline of the Sanyati Basin of Lake Kariba. *Insert* The location of Lake Kariba between Zambia and Zimbabwe

of human impacts known to occur along the shores of the basin. Water and periphytic diatom samples were collected monthly at the ten sites between May and July of 2005.

Notable human activities or developments within 500 m of the shoreline include residential areas, commercial aquacultural activities, maintenance of boats and boating activities, hotels and other tourist accommodation, roads and vehicles, urban development, industrial development, construction activities, sewage effluent disposal, domestic activities (washing and bathing) and effluent disposal from farming activities. To estimate relative degrees of disturbance among the sites, we scored the level of impact of each activity or development at each site qualitatively on a scale of 0 (not occurring at the site) through 1 (low) and 2 (medium) to 3 (high). An overall total human disturbance score was thus obtained, and each site was subsequently categorized as belonging to one of four categories: no evident disturbance (0), little disturbance (1–11), moderate disturbance (12–22) and much disturbance (23–33).

Five water samples (2-l bottles) were collected at each sampling site from different points along a stretch of about 100 m. All samples from each site were put into a 20-l bucket from which a 2-l sub-sample was taken for analysis of the concentrations of ammonium, nitrates, phosphates, total phosphorus (P) and sulphates. Water temperature, pH, dissolved oxygen, conductivity and turbidity were measured in situ. Temperature, pH and dissolved oxygen were measured with a mercury thermometer, a WTW 330i pH meter (Geotech Environmental Equipment, Denver, Colo.) and WTW Oxi 330 oxygen meter (Geotech Environmental Equipment), respectively.

The concentrations of ammonium, nitrates, phosphates, total P and sulphates were obtained using the spectrophotometric methods described by Madera et al. (1982). Analysis of variance (ANOVA) was used to test for differences between sites in the physical and chemical variables measured.

To sample for epiphytic diatoms, five plants of the submerged macrophyte *Vallisneria aethiopica* were randomly chosen from different points along a stretch of about 100 m at each site. The plants were cut underwater with scissors and gently brought to the surface, taking care not to disturb the biofilm on the plants. Three portions of leaf were obtained from each plant. The diatoms were separated from the leaf fragments by vigorously shaking the fragments for 1 min in 1-l of tap water and then lightly scraping each segment using a toothbrush after which a 100 ml sub-sample was preserved in Lugol's solution. In the laboratory, diatom valves were prepared for light microscopy using acid cleaning following the procedures of Biggs and Kilroy (2000). Two permanent Naphrax slide mounts were prepared for each sample. Diatoms were viewed under at a magnification of 1000× using immersion oil. A minimum of 300 diatom valves was counted from one of the slides prepared from each site. The diatoms were identified to the genus level using standard taxonomic texts.

The number of diatom genera obtained in each sample was recorded. The percentage relative abundance of each taxon in each sample was calculated as

$$\text{Relative abundance } \% = (n_{\mathrm{i}}/N) * 100$$

where n_{i} refers to the number of individuals of taxa i in the sample, and N refers to the total number of diatoms counted in the sample. Spearman rank correlations were evaluated using STATISTICA ver. 7 (StatSoft 2004) to determine the relationship between diatom abundance, human disturbance and water physical and chemical variables.

Diatom community diversity was calculated for each sample as Shannon's Diversity Index H' (Shannon and Weaver 1949). The mathematical equation for the Shannon-Wiener index is

$$H' = -\Sigma^{S} n_{\mathrm{i}}/n \ln n_{\mathrm{i}}/n$$

where H' is the community diversity, n is the total number of organisms in the sample, n_{i} is the number of individuals per taxon and S is the total number of taxa counted per sample.

An evenness index, the Pielou index (Krebs 1989; Clarke and Warwick 1994), was calculated for each sample using the formula

$$J' = H'/\mathrm{Log}\ S$$

in which H' is the Shannon-Wiener function and S refers to the number of taxa counted per sample. Kruskal-Wallis ANOVA was used to test for differences in diversity and evenness between sites. Spearman rank correlations were evaluated to determine the relationship (if any) that existed between the number of genera per site and the diversity and evenness indices and human disturbance and water physical and chemical variables.

We also calculated 16 diatom index of biotic integrity (DIBI) metrics using the environmental preferences of diatom species taken from published literature (van Dam et al. 1994; Hill et al. 2000) (Table 1). The mean environmental ratings for species within a genus were used as the environmental preferences of the diatom genera. The metrics were scored from 0 to 10, with decreasing scores corresponding to increasing human disturbance. The DIBI for each sample was determined by calculating the sum of the 16 metrics. The individual metrics and the total DIBI were then evaluated against human disturbance scores and water physical and chemical variables using the Spearman correlation.

Results

None of the sites was categorized as being highly disturbed (Table 2). Sites 1, 2 and 3 were categorized as having no human disturbance; Site 10 had a low human disturbance score, and the other six sites were moderately disturbed. The highest human disturbance score was obtained for Site 8 (Table 2).

The mean values for the physical and chemical variables at the ten sites are shown in Table 3.

Table 1 The metrics included in the diatom index of biotic integrity (DIBI)

Metric	Ecological indicator values[a]	Calculation	Range	Score[b]
Relative taxa richness metric		Number of algal genera/expected no. algal genera[d]	0–1	0–10
Dominant diatom metric		1–(No. dominant diatoms/total no. diatoms)	0–1	0–10
Motile diatoms metric[c]		1–(No. motile diatoms/total no. diatoms)	0–1	0–10
Acidophilic diatom metric	Mainly occurring at pH < 7	1–(No. acidophilic diatoms/total no. diatoms)	0–1	0–10
Circumneutral diatom metric	Mainly occurring at pH values about 7	1–(No. circumneutral diatoms/total no. diatoms)	0–1	0–10
Alkaliphilic diatom metric	Mainly occurring at pH > 7	1–(No. alkaliphilic diatoms/total no. diatoms)	0–1	0–10
Nitrogen-autotrophic diatom 1 metric 1 (–1)	Tolerating very small concentrations of organically bound nitrogen	1–(No. nitrogen-autophic diatoms 1/total no. diatoms)	0–1	0–10
Nitrogen-autotrophic diatom metric 2 (–2)	Tolerating elevated concentrations of organically bound nitrogen	1–[No. nitrogen-autophic (–2) diatoms/total no. diatoms]	0–1	0–10
Oxygen requirement 1 metric	Continuously high oxygen requirements (about 100% saturation)	1–(No. diatoms with continuously oxygen requirements/total no. diatoms)	0–1	0–10
Oxygen requirement 2 metric	Fairly high oxygen requirements (above 75% saturation)	1–(No. diatoms with fairly high oxygen requirements/total no. diatoms)	0–1	0–10
Oxygen requirement 3 metric	Moderate oxygen requirements (above 50% saturation)	1–(No. diatoms with moderate oxygen requirements/total no. diatoms)	0–1	0–10
Oxygen requirement 4 metric	Low oxygen requirements (above 30% saturation)	1–(No. diatoms with low oxygen requirements/total no. diatoms)	0–1	0–10
Oligo-mesotraphentic diatoms metric		1–(No. oligo-mesotraphentic diatoms/total no. diatoms)	0–1	0–10
Mesotraphentic diatoms metric		1–(No. mesotraphentic diatoms/total no. diatoms)	0–1	0–10
Meso-eutraphentic diatoms metric		1–(No. meso-eutraphentic diatoms/total no. diatoms)	0–1	0–10
Eutraphentic diatoms metric		1–(No. meso-eutraphentic diatoms/total no. diatoms)	0–1	0–10
			0–1	0–10
Range of potential DIBI scores				0–160

[a] The ecological indicator values were obtained from van Dam et al. (1994)

[b] Score range was obtained by multiplying the raw range by 10

[c] Motile diatom genera classification obtained from Hill et al. (2000)

[d] The expected number of genera was the observed maximum number of genera for each month

The only variables that differed significantly between the sites were pH and turbidity. The mean pH at Sites 2, 3 and 6 was significantly greater than that at Sites 4, 5, 7, 9 and 10, with the pH at Site 3 also being significantly greater than that of Site 8 (ANOVA, $F_{9,17} = 4.03$, $P < 0.05$). The turbidity at Site 2 was significantly greater than that at Sites 4 and 5, while that of Site 6 was significantly greater than that at Sites 3, 7, 8, 9 and 10 (ANOVA, $F_{9,17} = 2.55$, $P < 0.05$).

A total of 9993 diatoms were counted and 40 genera identified (Table 4). Nine genera, *Achnanthidium*, *Cocconeis*, *Diatoma*, *Encyonema*, *Fragilaria*, *Gomphonema*, *Navicula*, *Nitzschia*, and *Synedra* occurred at all ten sites. The two most abundant genera were *Achnanthidium* and *Gomphonema*, which comprised 23.4 and 42.9% of the total number of diatoms counted, respectively. *Achnanthidium* was most abundant at Sites 1 and 3, making up 63.1 and 41.1%, respectively, of the total number of diatoms at those sites and was generally found in relatively high numbers at all remote sites with no obvious human disturbance. *Gomphonema* dominated at all of the other eight sites, making up more than 50% of the total number of diatoms at Sites 4, 5, 6 and 8 (Table 4), all of which had moderate human disturbance scores.

The highest mean number of genera was obtained at Site 3 (20 ± 1.5) and the lowest at Site 4 (7.7 ± 1.5) (Table 5). Site 4 was the only site with a mean of fewer than ten diatom genera. The Shannon diversity index ranged from a high of 1.9 to a low of 0.9. Sites 2, 3, 10 and 11 showed relatively high levels of diatom diversity, while Sites 4 and 8 showed the lowest diversity of diatoms as well as the lowest evenness (Table 5). Taxa evenness ranged from 0.4 at Site 4 to 0.7 at Sites 3 and 9. There were no significant differences in the number of genera per site, the Shannon diversity index and the Pielou evenness index among the ten sites (Kruskal-Wallis ANOVA, $P > 0.05$). The number of genera per site and Shannon diversity was positively and significantly correlated with dissolved oxygen, while the number of genera was also significantly and negatively correlated with ammonium–nitrate concentration (Spearman correlation, $P < 0.05$).

The relative abundances of *Achnanthidium*, *Denticula*, *Pinnularia*, *Rhopalodia* and *Stauroneis* were negatively and significantly correlated with the disturbance score (Spearman Rank correlation, $P < 0.05$) (Table 6), suggesting that increases in human activities in the shallow marginal waters of the basin resulted in reduced abundance of these genera. The abundance of *Gomphonema* was significantly and positively correlated with the disturbance score (Spearman Rank correlation, $P < 0.05$) (Table 6), suggesting that *Gomphonema* was more tolerant of human impacts within the shallow marginal waters than other genera. The abundances of five genera (*Achnanthes*, *Cymbella*, *Denticula*, *Encyonema* and *Pinnularia*) were negatively and significantly correlated to total P, those of two genera (*Bacillaria* and *Mastogloia*) with nitrate–N (NO_3^-), those of two genera (*Diatoma* and *Navicula*) with ammonium–N (NH_4^+) and those of two genera

Table 2 Criteria for the human disturbance scores[a] within 500 m of the shore zone of Sanyati Basin

Activity	Site number									
	1	2	3	4	5	6	7	8	9	10
Residential area	0	0	0	0	0	0	0	3	1	1
Commercial aquaculture activities	0	0	0	3	0	3	0	2	0	0
Maintenance of boats and boating activities	0	0	0	2	3	1	3	2	3	2
Hotel/lodges/chalets	0	0	0	0	0	1	2	0	1	0
Road and vehicle density	0	0	0	3	2	2	3	3	3	2
Urban development	0	0	0	2	2	2	3	3	3	2
Industrial development	0	0	0	1	3	0	1	3	3	1
Active construction activities	0	0	0	3	3	0	0	3	3	2
Sewage effluent disposal	0	0	0	0	0	3	0	0	0	0
Effluent disposal from farming activities	0	0	0	3	0	2	0	0	0	0
Domestic human activities (washing and bathing)	0	0	0	0	0	0	0	3	0	0
Total disturbance score[b]	0	0	0	17	13	14	12	22	17	10
Human disturbance category[c]	N	N	N	M	M	M	M	M	M	L

[a] The impact of each activity or development at each site was assessed qualitatively on a scale of 0 (not occurring at the site) through 1 (low) and 2 (medium) to 3 (high)

[b] Overall total human disturbance score used for categorizing each site into one of four categories: 0, no evident disturbance; 1–11, little disturbance;12–22, moderate disturbance; 23–33,much disturbance

[c] The human disturbance category within which each site fell is represented by N = none or no disturbance, L = low, M = medium and H = high

Table 3 Mean (±SE) levels of selected physical and chemical variables of the water at the ten sites (n = 3 for variables at each site except where indicated otherwise)

Physical and chemical water variables	Site number 1	2	3	4	5	6	7	8	9	10
Temperature	25.5 ± 0.5	27.4 ± 0.9	26.0 ± 0.8	24.9 ± 0.2	24.4 ± 1.0	25.2 ± 1.7	26.2 ± 0.5	25.8 ± 0.8	25.3 ± 1.2	25.0 ± 0.9
Dissolved O_2 (mg l^{-1})	5.25 ± 0.35	5.75± 0.25	5.30 ± 0.30	4.00 ± 0.10	4.80 ± 0.50	4.85 ± 0.15	4.25 ± 0.35	4.30 (n = 1)	4.90 ± 0.50	4.45 ± 0.55
Conductivity (µS cm^{-1})	101.2 ± 1.4	99.2 ± 0.8	95.7 ± 1.3	99.2 ± 2.7	96.7 ± 0.6	95.4 ± 0.6	81.5 ± 17.0	97.1 ± 0.7	96.5 ± 0.6	95.1 ± 0.2
Total dissolved salts (mg l^{-1})	41.5 ± 0.5	40.5 ± 0.5	39.3 ± 0.3	40.3 ± 1.3	39.7 ± 0.3	39.0 ± 0.0	40.0 ± 0.0	40.0 ± 0.0	39.3 ± 0.3	39.0 ± 0.0
pH	7.7 ± 0.3	8.3 ± 0.1	8.6 ± 0.1	7.0 ± 0.6	6.7 ± 0.3	8.2 ± 0.4	7.1 ± 0.1	7.4 ± 0.1	7.0 ± 0.3	7.2 ± 0.1
Turbidity (NTU)	16.5 ± 1.5	4.4 ± 0.7	7.3 ± 1.3	15.6 ± 2.5	10.9 ± 3.4	19.4 ± 7.8	8.0 ± 2.1	2.1 ± 0.1	5.8 ± 1.5	5.6 ± 2.7
Ammonium–N (NH_4^+) (µg l^{-1})	62.7 (n = 1)	25.0 (n = 1)	31.7 ± 7.5 (n = 2)	48.5 ± 28.2 (n = 2)	18.8 ± 1.1 (n = 2)	30.8 ± 0.7 (n = 2)	31.7 ± 3.7 (n = 2)	21.6 ± 5.6 (n = 2)	20.7 ± 3.6 (n = 2)	12.2 ± 3.0 (n = 2)
Nitrate–N (NO_3^-) (µg l^{-1})	42.8 (n = 1)	27.6 (n = 1)	21.7 ± 11.0 (n = 2)	37.5 ± 25.3 (n = 2)	26.7 ± 3.5 (n = 2)	22.8 ± 14.2 (n = 2)	22.5 ± 13.9 (n = 2)	20.3 ± 7.7 (n = 2)	20.8 ± 10.7 (n = 2)	16.1 ± 8.0 (n = 2)
Phosphates (PO_4^{3-}) (µg l^{-1})	1.4 (n = 1)	1.4 (n = 1)	2.5 ± 0.4 (n = 2)	11.0 ± 5.2 (n = 2)	2.7 ± 2.1 (n = 2)	4.3 ± 2.2 (n = 2)	2.4 ± 1.4 (n = 2)	5.3 (n = 1)	7.8 ± 6.0 (n = 2)	2.9 ± 0.8 (n = 2)
Total phosphorous (µg l^{-1})	1.8 (n = 1)	1.4 (n = 1)	12.5 ± 9.6 (n = 2)	26.7 ± 10.4 (n = 2)	11.6 ± 8.5 (n = 2)	14.9 ± 3.6 (n = 2)	18.6 ± 0.9 (n = 2)	9.2 ± 3.9 (n = 2)	15.2 ± 1.4 (n = 2)	4.0 ± 3.9 (n = 2)
Sulphates SO_4^{2-} (mg l^{-1})	1.5 (n = 1)	1.2 (n = 1)	2.6 ± 1.5	4.1 ± 3.2	2.1 ± 1.3	2.3 ± 1.1	2.1 ± 1.3	2.0 ± 1.1	2.8 (n = 1)	1.8 ± 1.0

Table 4 Percentage relative abundances of periphytic diatoms associated with *Vallisneria aethiopica* in the shallow marginal waters of Sanyati Basin

Periphytic diatoms	Site number									
	1	2	3	4	5	6	7	8	9	10
Achnanthes	0.6	2.0	0.1	0.1	0.5	0.2		0.2	1.1	
Achnanthidium	63.1	20.5	41.1	0.4	16.1	7.4	19.8	9.7	23.7	27.5
Actinella			2.2							
Amphora	0.7	0.5	1.0	0.1		9.2	0.3	1.5	0.2	2.1
Aneumastis						0.1	0.3			
Aulacoseira		0.2	0.7	0.1	0.4	0.2	0.1		2.1	
Bacillaria			1.4		0.5	0.8	4.4		2.4	1.5
Cocconeis	0.4	2.9	11.4	20.3	3.6	0.8	0.3	0.6	1.8	0.5
Cyclotella	0.1				0.1		0.1		0.2	
Cymatopleura			0.1							
Cymbella	0.1	0.6	0.3		0.2	0.9	0.2	0.2		0.3
Denticula	0.3	2.5	0.9		0.3	1.6	0.3			0.8
Diatoma	0.1	0.5	0.2	0.3	0.5	0.3	0.5	3.1	3.2	2.1
Diatomella			3.6						0.2	
Didymosphenia			0.1							
Diploneis	0.1	0.2			0.1			0.2	0.1	0.3
Encyonema	2.3	2.0	1.2	0.1	0.8	1.1	0.4	0.8	1.4	1.8
Epithemia		0.2	0.4		0.2	0.1	0.1	0.3	0.2	
Eunotia		0.5			0.3		0.1	0.5	0.2	0.3
Fragilaria	1.9	4.3	2.0	2.1	3.0	3.3	3.4	1.4	2.1	2.5
Frustulia	1.0									
Gomphonema	16.0	45.5	10.3	69.0	56.1	60.1	47.2	72.2	32.9	35.9
Gyrosigma	0.3	0.2	0.1				0.1		0.1	0.1
Hantzschia									0.1	
Martyana			0.1							
Mastogloia	0.3	0.2	1.4		0.1		0.5	0.3	1.3	1.4
Melosira		0.2								
Navicula	3.9	4.6	3.3	1.3	4.3	4.5	4.5	3.7	11.1	4.7
Nitzschia	3.0	6.3	6.7	3.7	7.0	3.3	9.2	2.8	11.5	11.6
Opephora									0.1	
Pinnularia	0.7	1.1	0.5		0.5		0.4	0.9	0.4	0.4
Placoneis									0.1	
Pseudostaurosira			0.4	0.1			0.1			
Rhoicosphenia	0.1	0.2	0.6		0.7	1.7				0.3
Rhopalodia	1.2	0.8	2.9	0.1	0.3	0.3		0.2	0.3	0.5
Sellaphora										0.1
Stauroneis	2.5	3.2	1.9		1.4	0.3	1.9	1.1	1.1	2.2
Surirella		0.3	0.1			0.4		0.3	0.2	0.1
Synedra	1.2	1.1	4.7	2.4	3.3	3.8	6.0	0.3	2.0	3.0
Tabellaria	0.6		0.4							
Number of samples	2	2	3	3	3	3	3	2	3	3
Total no. of diatoms	726	653	1347	1005	1100	1166	1103	650	1062	1181
Number of taxa	22	25	30	14	23	21	23	20	27	23

(*Eunotia* and *Mastogloia*) with turbidity. Thus, the relative abundances of 13 diatom genera associated with *V. aethiopica* decreased with increasing disturbance score in the shallow waters of the Sanyati Basin.

Of the 16 DIBI metrics, 11 were significantly correlated with at least one of the 12 environmental variables (Table 7); 9 of the 16 metrics used in calculating the DIBI were significantly correlated with the DIBI (Table 7). Among the environmental variables the disturbance score was the only one that was significantly and inversely correlated with the DIBI (Table 7).

The DIBI scores ranged between 113.8 (Site 4) and 145.9 (Site1) (Table 8). There were significant differences in DIBI scores among the sites

Table 5 Mean number of genera, diversity and evenness (±SE) at ten sites along the shores of Sanyati Basin

Site	Number of genera	Shannon diversity (H')	Pielou evenness (J')
1	17.5 ± 2.5	1.4 ± 0.1	0.5 ± 0.1
2	19.0 ± 2.0	1.8 ± 0.2	0.6 ± 0.1
3	20.0 ± 1.5	1.9 ± 0.2	0.7 ± 0.0
4	7.7 ± 1.5	0.9 ± 0.2	0.4 ± 0.1
5	16.0 ± 1.5	1.5 ± 0.1	0.5 ± 0.0
6	14.7 ± 1.8	1.5 ± 0.3	0.6 ± 0.1
7	14.3 ± 3.3	1.6 ± 0.3	0.6 ± 0.1
8	14.0 ± 5.0	1.0 ± 0.6	0.4 ± 0.2
9	19.3 ± 1.2	1.9 ± 0.0	0.7 ± 0.0
10	17.7 ± 0.7	1.8 ± 0.1	0.6 ± 0.0

(ANOVA, $F_{9,\ 17} = 4.21$, $P = 0.005$). The DIBI scores at Sites 1 and 3 were significantly greater than those at Sites 2, 4, 5, 6, 7 and 8. Site 4 also had DIBI scores that were significantly lower than those at sites 7, 9 and 10. Thus, in general, remote sites with lower human activities had higher DIBI scores than those located where human activities were high. These data suggest that increases in human disturbances result in a decrease in the biological integrity of the diatom community associated with *V. aethiopica* in the shallow marginal water of Sanyati Basin.

Discussion

This study is the first to examine the responses of periphytic diatoms to human activities in a water body in Zimbabwe. Diatoms have been used successfully elsewhere to determine the ecological conditions of water bodies (Squires et al. 1979; Duncan and Blinn 1989; Bahls et al. 1992; Hardwick et al. 1992; Biggs and Hickey 1994; van Dam et al. 1994; Hill et al. 2000; Blinn and Bailey 2001; Köster and Hübener 2001). Most of the work on the use of diatoms has largely concentrated on epilithic diatoms in lotic systems. The present study has shown that periphytic diatoms on *V. aethiopica* may be used as tools to assess the impact of human activities on shallow inshore areas of a lentic system, Lake Kariba.

The most abundant genus at remote sites with no human disturbance was *Achnanthidium*, while at those sites with increased human activities *Gomphonema* dominated the diatom assemblage. The study showed that *Achnanthes*, *Cymbella*, *Denticula*, *Encyonema* and *Pinnularia* were sensitive to increased concentration of total P, *Bacillaria* and *Mastogloia* to an increase in nitrate–N, *Diatoma* and *Navicula* to an increase in ammonium–N and *Eunotia* and *Mastogloia* to turbidity. A number of other studies have also shown that diatom communities are affected by changes in physical and chemical variables, including changes in the concentrations of nutrients (Bahls et al. 1984; Charles 1985; Anderson et al. 1990).

The diatom assemblages from most of the sites located in remote areas and subjected to minimal human impact had relatively higher numbers of diatom genera and higher indices of diversity and community evenness than sites located in areas with relatively higher levels of human disturbance. The use of biotic indices is a water quality assessment approach that has been developed to avoid shortcomings associated with using the indicator species and community structure (richness, diversity, evenness) approaches (Hill et al. 2000). We found that although the number of genera, diversity and evenness tended to be higher at remote areas with minimal human disturbance, there were no significant differences among sites; in addition, the number of genera, diversity and evenness showed no significant correlations with the level of human disturbance. Unlike the indices based on community structure, the DIBI was more responsive to disturbance and showed a significant and inverse correlation with human disturbance.

In this study generic rather than species level resolution was used largely due to the limited information available on both the taxonomy of diatoms and diatoms in general in the Southern Africa region as well as the need to develop an easy-to-use, cost-effective diatom-based monitoring system for the lake that can be used by non-experts in algal taxonomy. The study revealed that human impact on the shallow water zones of Lake Kariba could potentially be evaluated using genus level taxonomic resolution of diatoms. Although there is some debate on the use of genus versus species level identification for assessing the quality of freshwater environments,

Table 6 Spearman correlation coefficients[a] for the relationship between percentage relative abundances of the periphytic diatoms, disturbance scores and selected physical and chemical characteristics of the water in the shallow marginal zones of Sanyati Basin

	Disturbance score	Temperature	Dissolved O_2	Conductivity	Total dissolved solids	pH	Turbidity	NH_4^+	NO_3^-	PO_4^{3-}	Total phosphorous	SO_4^{2-}
Achnanthes	0.01	0.26	0.21	**0.39**	0.30	0.02	–0.03	–0.02	0.45	0.31	**–0.49**	–0.44
Achnanthidium	**–0.60**	0.26	0.23	–0.02	0.14	0.14	–0.01	–0.04	–0.03	–0.14	–0.42	–0.16
Actinella	–0.26	0.13		–0.23	–0.19	0.25	–0.05	0.30	–0.21	–0.12	0.35	0.36
Amphora	–0.04	**0.45**	–0.32	–0.23	–0.10	0.29	–0.12	0.09	–0.12	–0.22	–0.07	0.04
Aneumastis	0.03	–0.22	–0.01	0.12	–0.04	–0.03	0.24					
Aulacoseira	0.05	0.10	0.31	–0.15	–0.31	0.21	–0.15	0.20	0.07	0.20	0.20	0.14
Bacillaria	–0.09	**–0.44**	0.37	–0.20	–0.28	–0.05	–0.24	0.07	**–0.66**	0.10	0.33	0.41
Cocconeis	0.15	–0.16	0.18	0.22	–0.03	0.03	0.09	–0.16	0.12	0.45	–0.07	–0.08
Cyclotella	–0.01	–0.07	0.13	0.19	0.15	–0.07	0.35	–0.16	0.12	–0.35	–0.21	–0.36
Cymatopleura	–0.26	–0.19	0.32	–0.30	–0.19	0.23	–0.09					
Cymbella	–0.13	0.38	0.03	0.02	–0.05	0.29	0.22	–0.10	0.05	0.29	**–0.52**	–0.33
Denticulata	**–0.46**	–0.07	**0.50**	0.00	–0.06	0.15	–0.13	0.04	0.22	0.00	**–0.64**	–0.25
Diatoma	0.18	–0.10	–0.09	–0.02	–0.08	–0.28	–0.33	**–0.61**	–0.36	0.10	–0.15	–0.07
Diatomella	–0.04	–0.33	0.32	–0.16	–0.06	–0.02	–0.24	–0.05	–0.26	0.26	0.12	0.08
Didymosphenia	–0.26	0.24	0.09	0.18	0.12	0.33	0.03	–0.05	0.21	0.21	–0.26	–0.15
Diploneis	–0.10	0.22	–0.07	0.04	0.06	–0.16	–0.28	–0.30	0.27	0.14	–0.46	–0.20
Encyonema	–0.33	0.18	0.14	0.01	–0.01	0.15	–0.17	–0.06	–0.21	0.08	**–0.47**	–0.05
Epithemia	0.10	0.05	0.32	–0.10	–0.11	0.08	–0.24	–0.28	0.02	–0.07	–0.05	–0.20
Eunotia	0.09	–0.12	0.22	–0.01	0.06	–0.13	**–0.53**	–0.31	–0.37	0.20	–0.05	–0.10
Fragilaria	–0.16	–0.26	0.38	0.21	0.15	0.02	–0.14	0.27	–0.42	–0.09	0.43	**0.60**
Frustulia	–0.37	–0.00	0.22	**0.40**	**0.45**	0.09	0.34	0.35	0.35	–0.23	–0.30	0.00
Gomphonema	**0.58**	–0.02	–0.38	–0.15	–0.16	–0.27	–0.08	0.01	0.15	0.05	0.33	–0.04
Gyrosigma	–0.33	0.15	0.34	0.36	0.24	0.19	–0.00	–0.43	0.00	–0.04	–0.20	–0.06
Hantzschia	0.22	0.28	–0.13	–0.03	–0.19	–0.15	–0.09	–0.26	0.16	–0.23	0.02	
Martyana	–0.26	–0.19	0.32	–0.30	–0.19	0.23	–0.09					
Mastogloia	–0.20	–0.20	0.22	–0.26	–0.21	–0.06	**–0.46**	–0.31	**–0.56**	0.06	0.23	0.27
Melosira	–0.26	0.33	0.26	0.20	0.12	0.18	–0.16	0.02	0.02	0.30	–0.35	–0.08
Navicula	–0.02	0.02	0.16	0.07	–0.06	–0.15	–0.25	**–0.59**	–0.15	0.07	–0.41	–0.21
Nitzschia	–0.08	–0.13	0.25	0.05	0.03	–0.05	–0.28	–0.39	–0.15	0.08	–0.23	–0.12
Opephora	0.22	–0.08	0.22	–0.14	–0.19	0.10	0.00					
Pinnularia	**–0.43**	**0.45**	0.25	0.01	0.06	0.22	–0.28	–0.33	0.13	0.04	**–0.50**	–0.35
Placoneis	0.22	–0.08	0.22	–0.14	–0.19	0.10	0.00		–0.26			
Pseudostaurosira	–0.06	–0.23	0.01	0.13	0.16	–0.02	0.17	–0.05	0.21	0.26	0.12	0.08
Rhoicosphenia	–0.31	0.31	0.14	–0.26	–0.27	**0.41**	0.19	0.02	–0.17	–0.02	–0.20	0.00
Rhopalodia	**–0.46**	–0.34	**0.62**	0.00	–0.04	0.33	–0.29	0.05	–0.20	–0.09	0.07	0.36
Sellaphora	–0.13	–0.23		–0.18	–0.19	0.03	–0.23	–0.40	–0.40	0.00	–0.12	0.08
Stauroneis	**–0.57**	0.15	0.25	–0.06	0.15	–0.02	–0.25	–0.24	–0.27	–0.16	–0.19	–0.01
Surirella	–0.03	–0.06	0.43	–0.08	–0.09	0.35	–0.33	–0.41	–0.15	0.43	–0.39	–0.16
Synedra	–0.08	**–0.50**	0.25	–0.03	–0.17	0.01	0.11	0.18	–0.44	0.11	0.39	0.36
Tabellaria	–0.37	0.02	0.31	–0.10	–0.06	**0.40**	–0.05	–0.05	0.21	0.21	–0.26	–0.15

[a] Significant correlations ($P < 0.05$) are presented in bold type

Table 7 Spearman correlation coefficients[a] for the relationship between the DIBI and its component metrics

Metric	Disturbance score	Temperature	Dissolved O_2	Conductivity	Total dissolved solids	pH	Turbidity	NH_4^+	NO_3^-	PO_4^{2-}	Total phosphorous	SO_4^{2-}	DIBI
Relative taxa richness	–0.36	0.11	**0.53**	–0.09	–0.12	0.30	–0.38	–0.38	–0.34	0.10	–0.23	–0.34	**0.68**
Dominant diatom metric	–0.37	0.08	0.32	0.00	–0.09	0.12	–0.24	–0.36	–0.27	0.10	–0.42	–0.27	**0.59**
Motile diatom	**0.50**	0.07	**–0.70**	–0.36	–0.32	–0.24	0.22	0.17	0.11	–0.19	0.40	0.11	–0.33
Acidophilic diatom	**0.57**	–0.29	**–0.54**	–0.13	–0.22	–0.28	0.35	0.22	–0.11	–0.05	**0.55**	–0.11	**–0.55**
Circumneutral diatom	**–0.73**	0.09	**0.60**	0.26	0.28	**0.41**	0.04	–0.02	–0.17	–0.05	–0.35	–0.17	**0.73**
Alkaliphilc	0.36	–0.08	**–0.59**	–0.27	–0.09	**–0.54**	–0.04	0.02	0.03	–0.22	0.23	0.03	–0.06
Nitrogen-autotrophic diatom (–1)	**–0.50**	0.04	0.29	0.15	0.16	0.22	0.13	–0.02	–0.18	–0.11	–0.30	–0.18	**0.82**
Nitrogen-autotrophic diatom (–2)	–0.10	0.06	–0.14	–0.06	0.18	–0.14	0.09	0.39	0.34	–0.36	0.12	0.34	–0.09
Oxygen requirement 1	**–0.52**	0.05	0.29	0.15	0.16	0.23	0.12	–0.02	–0.18	–0.11	–0.30	–0.18	**0.82**
Oxygen requirement 2	–0.07	0.04	–0.20	0.17	0.29	–0.18	0.28	0.37	0.30	–0.19	0.23	0.30	–0.25
Oxygen requirement 3	–0.15	0.16	–0.18	–0.22	0.03	–0.03	–0.09	0.16	–0.12	–0.45	0.07	–0.12	0.2
Oxygen requirement 4	0.09	**0.44**	–0.37	0.20	0.28	0.05	0.24	–0.07	**0.66**	–0.10	–0.33	**0.66**	–0.27
Oligo-mesotraphentic diatoms	**0.57**	–0.29	**–0.54**	–0.13	–0.22	–0.28	0.35	0.22	–0.11	–0.05	**0.55**	–0.114	**–0.55**
Mesotraphentic diatoms	**–0.72**	0.09	**0.55**	0.26	0.27	0.34	–0.03	–0.13	–0.26	–0.08	–0.32	–0.26	**0.77**
Meso-eutraphentic diatoms	**0.45**	–0.21	**–0.63**	–0.11	–0.03	**–0.50**	0.21	0.22	0.20	–0.09	0.45	0.20	**–0.48**
Eutraphentic diatoms	0.02	0.17	–0.23	–0.09	0.14	–0.12	0.03	0.23	0.28	–0.41	–0.14	0.28	–0.02
DIBI	**–0.64**	0.13	0.27	–0.01	0.11	0.14	0.06	–0.02	–0.16	–0.17	–0.32	–0.13	

[a] Significant correlations ($P < 0.05$) are in bold

Table 8 DIBI scores obtained from diatoms associated with *V. aethiopica* along the shallow marginal waters of Sanyati Basin

Site	*n*	Mean ± SE	DIBI score	
			Minimum	Maximum
1	2	142.9 ± 4.7	140.0	145.9
2	2	124.9 ± 4.7	118.9	130.9
3	3	140.9 ± 3.9	132.0	148.4
4	3	115.7 ± 3.9	113.8	117.2
5	3	126.0 ± 3.9	119.1	133.2
6	3	123.1 ± 3.9	117.1	127.3
7	3	129.0 ± 3.9	122.0	137.5
8	2	120.8 ± 4.7	113.7	127.9
9	3	130.6 ± 3.9	126.7	136.5
10	3	132.8 ± 3.9	125.5	138.6

a number of studies have found that while some information is lost, genus-based indices generally give acceptable indications of environmental quality (Kelly et al. 1995; Hill et al. 2001; Wunsan et al. 2002). Periphytic diatoms associated with *V. aethiopica* are therefore a potential tool that may be used to determine the ecological conditions of the shallow water margins in Sanyati Basin, and there is need for further exploration of their use for routine monitoring of the impact of anthropogenic activities, especially the development of a composite DIBI.

Conclusion

We report here the preliminary results of an ongoing study on the use of diatoms and macroinvertebrates as a tool for assessing ecological conditions within the shallow marginal waters of a large manmade reservoir, Lake Kariba. Although further work is necessary, this study shows that the diatom communities associated with *V. aethiopica* respond to differences and variations in human-induced effects in the shallow waters, thereby making them candidates for further development as freshwater biomonitoring tools in Zimbabwe.

Acknowledgements This study was financed by the Water Research Fund for Southern Africa (WARFSA). We are also grateful for the support provided by the technical team of the University of Zimbabwe Lake Kariba Research Station. We would also like to thank our colleagues at the Zoology Department, Freshwater Research Unit University of Cape Town, who provided a stimulating and welcome environment for the initial compilation of this work.

References

Anderson NJ, Ripper B, Stevenson AC (1990) Change to a diatom assemblage in a eutrophic lake following point source nutrition redirection: a palaeolimnological approach. Freshw Biol 23:205–217

Bahls LL (1993) Periphyton bioassessment methods for Montana Streams. Montana Water Quality Bureau, Department of Health and Environmental Science, Helena, Montana

Bahls LL, Weber EE, Jarvie JO (1984) Ecology and distribution of major diatom ecotypes in the southern Fort Union Coal Region of Montana. Geological Survey Professional Paper 1289, Washington D.C.

Bahls LL, Bukantis R, Tralles S (1992) Benchmark biology of Montana reference streams. Montana Water Quality Bureau, Department of Health and Environmental Sciences, Helena, Montana

Biggs BJF, Hickey CW (1994) Periphyton responses to a hydraulic gradient in a regulated river in New Zealand. Freshw Biol 32:49–59

Biggs BJF, Kilroy C (2000) Stream periphyton monitoring manual. NIWA, Christchurch, New Zealand

Blinn DW, Bailey PCE (2001) Land-use influence on stream water quality and diatom communities in Victoria, Australia: a response to secondary salinization. Hydrobiologia 466:231–244

Charles DF (1985) Relationship between surface sediment diatom assemblages and lake water characteristics in Adirondack lakes. Ecology 66:994–1011

Clarke KR, Warwick RM (1994) Change in marine communities, an approach to statistical analysis and interpretation. Natural Environment Research Council, UK

Dixit SS, Smol JP, Kingston JC, Charles DF (1992) Diatoms: powerful indicators of environmental change. Environ Sci Technol 26:21–33

Duncan SW, Blinn DW (1989) Importance of physical variables on the seasonal dynamics of epilithic algae in a highly shaded canyon stream. J Phycol 25:455–461

Gaufin AR (1973) Use of aquatic invertebrates in the assessment of water quality. In: Cairns J, Dickson KL (eds) Biological methods for assessment of water quality: 75th Annu Meet Am Soc Testing Materials. American Society for Testing and Materials, Philadelphia, pp 96–116

Hardwick G, Blinn DW, Usher HD (1992) Epiphytic diatoms on *Cladophora glomerata* in the Colorado River: longitudinal and vertical distribution in a regulated river. Southwest Nat 37:148–156

Hill BH, Herlihy AT, Kaufmann PR, Stevenson RJ, McCormick FH, Johnson CB (2000) Use of periphyton assemblage data as an index of biotic integrity. J N Am Benthol Soc 19:50–67

Hill BH, Stevenson RJ, Pan Y, Herlihy AT, Kaufmann PR, Johnson CB (2001) Comparison of correlations between environmental characteristics and stream diatom assemblages characterized at genus and species levels. J N Am Benthol Soc 20:299–310

Kelly MG, Penny CJ, Whitton BA (1995) Comparative performance of benthic diatom indices used to assess river water quality. Hydrobiologia 302:179–188

Köster D, Hübener T (2001) Application of diatom indices in a planted ditch constructed for tertiary sewage treatment in Schwaan, Germany. Internat Rev Hydrobiol 86:241–252

Krebs CJ (1989) Ecological methodology. Harper Collins Publishers, New York

Lowe RL, Pan Y (1996) Benthic algal communities as biological monitors. In: Stevenson RJ, Bothwell ML, Lowe RL (eds) Algal ecology: freshwater benthic ecosystems. Academic Press, New York, pp 705–739

Madera V, Allen HE, Minear RA (1982) Non-metallic constituents. In: Suess MJ (ed) Examination of water pollution control: vol 2. Physical, chemical and radiological examination. Pergamon Press, Oxford, pp 169–357

Patrick R, Palavage DM (1994) The value of species as indicators of water quality. Proc Acad Nat Sci Philadelphia 145:55–92

Shannon CE, Weaver W (1949) The mathematical theory of communication. University of Illinois Press, Urbana

Squires LE, Rushforth SR, Brotherson JD (1979) Algal response to a thermal effluent: study of a power station on the Provo River, Utah, USA. Hydrobiologia 63:17–32

StatSoft, Inc. (2004) STATISTICA (data analysis software system), version 7. www.statsoft.com

Stevenson RJ, Bahls LL (1999) Periphyton protocols. In: Barbour MT, Gerritsen J, Synder BD, Stribling JB (eds) Rapid bioassessment protocols: for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates, and fish, 2nd edn. EPA 841-B-99-002. U.S. Environmental Protection Agency, Office of Water, Washington D.C., pp 6-1 to 6-22

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

Weber CI (1973) Biological monitoring of the aquatic environment. In: Cairns J, Dickson KL (eds) Biological methods for assessment of water quality: 75th Ann Meet Am Soc Testing Materials. American Society for Testing and Materials, Philadelphia, pp 46–60

Werner D (ed) (1977) The biology of diatoms. Blackwell Scientific, Oxford

Wunsan S, Cattaneo A, Bourassa N (2002) Comparing diatom species, genera and size in biomonitoring: a case study from streams in the Laurentians (Québec, Canada). Freshw Biol 47:325–340