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Diatom communities in streams draining urban areas: community structure in relation to environmental variables

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Abstract: Diatoms are good indicators of ecological conditions in lotic systems. The objective of this study was to assess responses of benthic diatoms to changes in water quality in tropical streams draining Chinhoyi Town, Zimbabwe. Eight sites were selected to evaluate the impact of sewage effluent on water quality and the associated diatom communities. Diatom and water quality sampling were conducted once in January, March, May, June, and August in 2012. Canonical correspondence analysis (CCA) was used to determine environmental gradients along which species vary with physical and chemical variables. As pollution increased (i.e., increase in nutrients, conductivity, and metal levels, and decrease in pH and dissolved oxygen levels), low or moderate pollution tolerant species such as *Cymbela tumida, Cocconeis placentula,* and *Eunotia formica* were replaced by high pollution tolerant species such as *Gophonema. parvulum, Navicula gregalis,* and *Nitzschia palea*. The autecological data presented in this study corroborates other studies from tropical regions and further contributes to our understanding of how diatoms are distributed in tropical lotic systems with respect to environmental variables.

Resumen: Las diatomeas son buenos indicadores de las condiciones ecológicas en sistemas lóticos. El objetivo del estudio fue evaluar las respuestas de las diatomeas bentónicas a cambios enla calidad del agua en los arroyos tropicales que drenan el poblado de Chinhoyi, Zimbabue. Se seleccionaron ocho sitios para evaluarel impactodel flujo de aguas negras sobre la calidad del aguay las comunidades asociadas de diatomeas. El muestreo de las diatomeas y de la calidad de agua se llevó a cabo en enero, marzo, mayo, junio y agostode 2012. Se usó un Análisis Canónico de Correspondenciapara determinarlos gradientes ambientales a lo largo de los cuales varían las especies con las variables físicas y químicas. Conforme aumentó la contaminación (i.e., aumento enlos niveles de nutrimentos, conductividad y metales, yreduccióndel pH y los niveles de oxígeno disuelto), las especies poco tolerantes a la contaminación como *Cymbela tumida, Cocconeis placentula* y *Eunotia formica* fueron reemplazadas porespecies con una tolerancia alta a la contaminación, tales como *Gophonema parvulum*, *Navicula gregalis* y *Nitzschia palea*. Los datos autoecológicos presentadosen esteestudio corroboran los de otros estudios realizados en regiones tropicales y contribuyen a nuestro entendimiento de cómo las diatomeas se distribuyenen sistemas lóticos tropicalescon respectoavariables ambientales.

Resumo: Em sistemas lóticos, as diatomáceas são bons indicadores das condições ecológicas. O objetivo deste estudo foi avaliar as respostas de diatomáceas bentónicas a mudanças na qualidade de cursos de água tropicais drenando a cidade de Chinhoyi no Zimbabwe. Para avaliar o impacto do efluente de esgoto na qualidade da água e as comunidades de diatomáceas associadas foram selecionados oito locais. A amostragem das diatomáceas e da qualidade da água foi realizada uma vez em janeiro, março, maio, junho e agostode 2012. A análise de correspondência canónica (CCA) foi utilizada para determinar os gradientes

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ambientais ao longo do qual as espécies variam de acordo com as variáveis físicas e químicas. Como a poluição aumentou (i.e. aumento de nutrientes, a condutividade, e níveis de metais, assim como, diminuição do pH e níveis de oxigénio dissolvido), espécies tolerantes a níveis baixos ou moderados de poluição, tais como a Cymbela tumida, *Cocconeis placentula* e *Eunotia formica* foram substituídas por espécies tolerantes a alta poluição tais como a *Gophonema parvulum*, *Navicula gregalis* e *Nitzschia palea*. Os dadosautecológicos apresentados neste estudo corroboram outros estudos de regiões tropicais e ainda contribuíram para a nossa compreensão de como as diatomáceas são distribuídos em sistemas lóticos tropicais no que diz respeito às variáveis ambientais.

Key words: Bioindicators, diatoms, eutrophication, pollution, tropical lotic systems.

Introduction

Periphyton communities are a fundamental part of biota of lotic systems (Azim *et al.* 2005; Taylor *et al.* 2007a, b; Wehr & Sheath 2003). They are solar-powered biogeochemical reactors, biogenic habitats, hydraulic roughness elements, early warning systems for environmental degradation, and troves of biodiversity (Larned 2010). Thus, they are important communities that are useful for assessment of ecological conditions in lotic systems (Harding *et al.* 2005). In particular, diatoms communities, which constitute the major part of periphyton communities, are composed of a large number of species with various ecological tolerances and preferences, thus, constituting a well-adapted biological model for environmental monitoring (Azim *et al.* 2005; Bere 2014; Bere & Tundisi 2009; 2010a, b, 2011a-e, Gómez & Licursi 2001; Nautiyal *et al.* 2000; USEPA 2001; Wehr & Sheath 2003).

Diatom community structures in streams are responsive to multiple factors prevailing at different temporal and spatial scales (Pan *et al.* 1996). These factors include water chemistry, substrate, current velocity, light, grazing, and temperature (Charles 2003; Pan *et al.* 1996; Potapova & Charles 2003, 2005; Round 1991). Most of these factors depend strongly on climate, geology, topography, land-use and other landscape characteristics, and, therefore, diatom communities are similar within ecological regions defined by these characteristics (Pan *et al.* 1996).

In addition, human land-use activities act to change both local and regional variables affecting the resultant diatom communities. For example, nutrient concentration, particularly phosphorus, has been shown to increase with urban development, associated with storm water runoff (Duong *et al.* 2006; Walker & Pan 2006). Increase in nutrient concentration is also caused by other catchment activities such as agriculture, or by point sources such as sewage treatment plants and other diffuse sources. Winter & Duthie (2000) showed that the diatom community composition along an urban-rural gradient was correlated to total phosphorus and total nitrogen.

Most of these studies have been carried out in temperate regions and few studies have been carried out in tropical streams, especially in Southern Africa. In particular, studies relating diatom communities to environmental variables, and hence their potential role as bioindicators, are few in Zimbabwe. Phiri *et al.* (2007) studied periphytic diatoms attached to the leaves of the submerged macrophyte *Vallisneria aethiopica* in the shallow waters of the Sanyati Basin in Lake Kariba, Zimbabwe, and concluded that diatoms may potentially be useful in assessing ecological conditions or the impact of human activities within the shallow marginal waters of the lake. Besides that study, there are no other detailed studies exploring the role of environmental variables in determining diatom communities and their potential use as indicators of water quality in aquatic systems in Zimbabwe.

Due to lack of information on ecological preferences and tolerances of diatoms in Zimbabwe, diatom-based biotic indices developed in temperate regions are often applied to assess ecological conditions in tropical context. However, there is evidence that diatom metrics or indices developed in one geographic area are less successful when applied in other areas (Pipp 2002). This is due not only to the floristic differences among regions (Pan *et al.* 1996; Taylor *et al.* 2007a, b), but also to the environmental differences that modify species responses to water-quality characteristics (Potapova

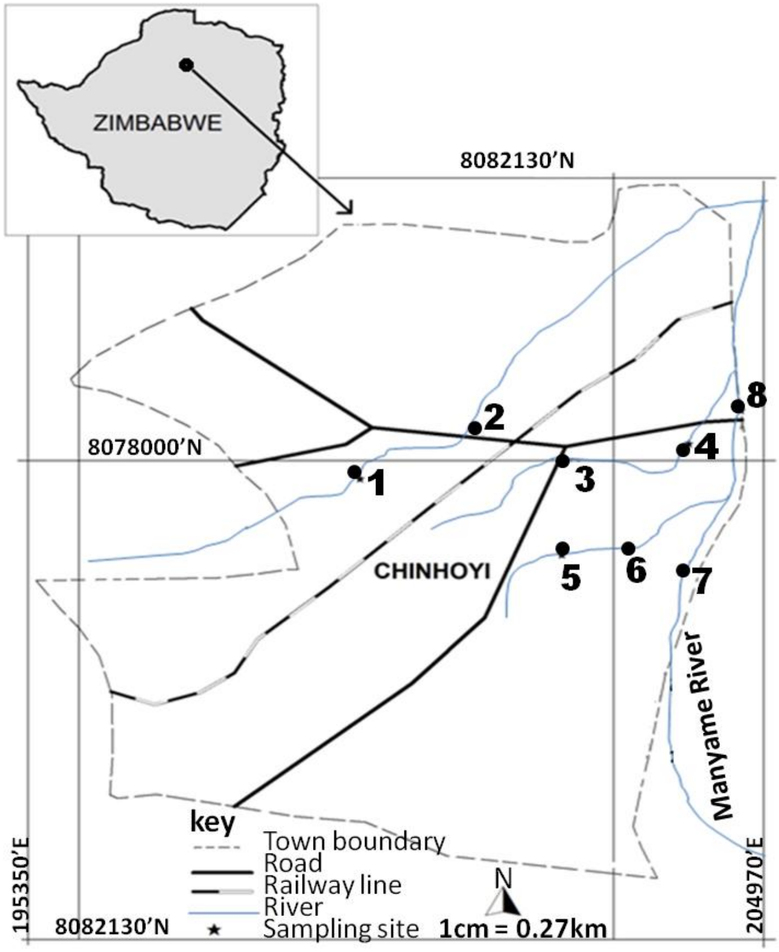

Fig. 1. Location of sampling sites in the study area. Sites 1, 2, 3, and 5 were moderately polluted, sites 4 and 6 were highly polluted as they located in close proximity to sewage effluent discharge points, and site 7 and 8 were relatively less polluted.

& Charles 2005). Thus, the objective of this study was to assess response of benthic diatoms to changes in water quality in tropical streams draining Chinhoyi Town, Zimbabwe.

Materials and methods

Study area and study design

The study was carried out in four streams draining the town of Chinhoyi in northern Zimbabwe (Fig. 1). The study area has an average annual temperature of 24.5 ± 5.1°C, with a mean monthly maximum of 29.9 ± 6.5 °C recorded in October and November and a mean monthly minimum of 18.9 ± 5.8 °C recorded in July (Meteorological Services Department of Zimbabwe; data from 1965 - 2012). In 2012, the population of Chinhoyi was estimated to be 79,368 inhabitants by the Zimbabwe National Statistics Agency (ZNSA). Due to population growth, the capacity of municipal sewage treatment facilities has been exceeded. Poor maintenance and breakdowns of these facilities are also very common because of the financial constrains currently facing the municipality. Therefore, streams in the study area receive untreated or semi-treated effluent from sewage treatment plants and bust sewage pipes as well as other diffuse sources as they pass through the town of Chinhoyi.

Eight sites were randomly established in different streams draining Chinhoyi Town (Fig. 1). Sampling sites were selected to evaluate the impact of a breakdown in municipal service delivery (especially sewage treatment and associated infrastructure and refuse collection) on water quality and subsequently diatom communities in streams draining Chinhoyi town. True reference sites were difficult to establish as two of the streams (Coldstream and Katanga Stream) start in an urban area that is characterised by flows of sewage from bust sewage pipes and uncollected refuse scatted across the entire urban area. The upper reaches of Muzari Stream that were not affected by urbanisation were not accessible. Thus, all sampling sites were affected by pollution in one way or the other.

Site 1 was located in the upstream reaches of Muzari Stream in low density suburbs that were expected to be relatively less polluted while site 2 was located in town centre where uncollected garbage and effluent from bust sewage pipes finds its way into the stream. Stream bank cultivation was common along stretches of the stream before site 1. Sites 4 and 6 were located just downstream of sewage effluent discharge points in Cold Stream and Katanga Stream respectively. Heavy overload, the obsolete nature and constant breakdowns of the sewage treatment facilities in close proximity to sites 4 and 6 implies that raw or semi-treated sewage effluent is always flowing through these sites as was observed on all field sampling trips. Sites 3 and 5 were located further upstream of sites 4 and 6 respectively. Sites 3 and 5 were in turn affected by sewage effluent from bust pipes, pollutants from uncollected refuse, as well as other diffuse sources of pollution. Site 7 was located upstream of the large Manyame River in a relatively less polluted area while site 8 was located further downstream along the same river. Large flow volumes in the Manyame River (the upper reaches of which drains less polluted commercial farms) are expected to have a dilution effects on pollutants at sites 7 and 8. Diatom and water quality samplings were conducted once in January and March (rainy season), and May, June, and August (dry season) during 2012. Sites 1, 3, and 5 dried out during the subsequent months following August sampling; hence, the study was concluded in August.

Field sampling

Twelve physical and chemical variables were measured during the study period. At each site, dissolved oxygen (DO), electrical conductivity, temperature, pH, and turbidity were measured in the middle of the stream at a depth of 20 to 30 cm below the surface of the water using portable probes (YSI, Yellow Springs, Ohio, USA). The percentage riparian vegetation cover was visually estimated at each site over 20 to 30 m riparian width. Water samples were collected at each site at a depth of 20 - 30 cm below the surface of the water during the day into acid-cleaned 100 ml polyethylene containers (APHA 1988). Epilithic diatoms were sampled at each site by brushing stones with a toothbrush. Prior to sampling of epilithic surfaces, all substrata were gently shaken in stream water to remove any loosely attached sediments and non-epilithic diatoms. At least five pebble-to-cobble sized stones were randomly collected at each sampling site and brushed, and the resulting diatom suspensions were pooled to form a single sample, which was then put in a labelled plastic bottle.

Laboratory analysis

The concentrations of ammonium, nitrites, phosphates, iron, and manganese were determined using a Hach DR/2010 spectrophotometer (Hach Company, 1996 - 2000). Calcium levels were determined by ethylenediamine tetra-acetic acid (EDTA) titrimetric method following APHA (1988). Subsamples of the diatom suspensions were cleaned of organic material using wet combustion with concentrated sulphuric acid and mounted in Naphrax (Northern Biological supplies Ltd., UK, RI = 1.74) following Biggs & Kilroy (2000). Three replicate slides were prepared for each sample. A total of 250 - 600 valves per sample (based on counting efficiency determination method by Pappas & Stoermer (1996)) were identified and counted using a phase-contrast light microscope (×1000; Leica Microsystems, Wetzlar GmbH, Type – 020-519.503 LB30T, Germany). The diatoms were identified to species level based mainly on studies from South Africa (Taylor *et al.* 2007c); studies from other tropical regions were consulted when necessary (e.g. Metzeltin & Lange-Bertalot 1998, 2007).

Data analysis

The mean and standard deviation of physical and chemical variables were calculated for each sampling site during the study period (January to August 2012). Multivariate data analyses were performed on the diatom community data to explore the main gradients of floristic variation and to detect and visualize similarities in diatom samples. Diatom counts from each site were expressed as relative abundances. Input for multivariate analysis included the diatom taxa that were present in a minimum of two samples and had a relative abundance of ≥ 1 % in at least one sample. This was done in order to eliminate the effects of rare species. Preliminary detrended correspondence analysis (DCA) was applied on diatom data set to determine the length of the gradient. The DCA revealed that the gradient was greater than three standard deviation units, justifying the use of unimodal ordination techniques (Ter Braak & Verdonschot 1995). Thus, canonical correspondence analysis (CCA) was performed to relate diatom community structure to simultaneous effects of predictor environmental variables, and to explore the relationship amongst and between species and predictor variables. Preliminary CCA identified collinear variables and selected a subset on inspection of variance inflation factors (VIF < 20; Ter Braak & Šmilauer 2002). Monte Carlo permutation tests (999 unrestricted permutations, $P \leq 0.05$) were used to test the significance of the axis and determine if the selected environmental variables could explain nearly as much variation in the diatom community structure as all the 12 environmental variables combined. DCA and CCAs were performed using CANOCO version 4.5 (Ter Braak & Šmilauer 2002).

Results

Physico-chemical variables

Temperature was relatively low in winter months, May and June, compared to the rest of the months. Temperature was comparable among sampling sites for all the sampling periods, though sites 1, 2, and 3, with high vegetation cover, generally tended to be cooler compared to the rest of the sites (Table 1). Conductivity, DO, pH, turbidity, nitrite, ammonium, phosphate, calcium, iron, and manganese levels were comparable among the sampling periods. The pH was also comparable among sites, though it tended to be generally low at sites 4 and 6, which were affected by sewage effluent, compared to the rest of the sites. In addition, turbidity, nitrite, and phosphate were relatively high and DO was relatively low at sites 4 and 6 compared to the rest of the sites. Ammonium and manganese levels were relatively high at sites 4, 5 and 6 compared to the rest of the sites. Conductivity was relatively low at Manyame River sites 7 and 8 where large flow volumes of 'clean water' had a dilution effects on pollutants compared to the rest of the sites. Calcium levels were relatively high at sites 1, 2, and 3 compared to the rest of the sites. Iron levels were relatively high at site 4.

Community composition

A total of 101 diatom species belonging to 35 genera were recorded in 39 samples. All the sites were subject to some form of pollution (agricultural or urban); hence, species distribution was strongly biased towards those that are cosmopolitan and tolerant of elevated or slightly elevated levels of pollution. The first four CCA axes accounted for 80.5 % of the total variance in the community due to measured environmental variables. Axis 1 and 2 significantly explained 29.6 % and 24.1 % respectively of the diatom species variance (Monte Carlo unrestricted permutation, $P < 0.05$) (Fig. 2). Conductivity and nitrite levels (the latter was positively correlated with turbidity, ammonium, phosphate, and manganese) were positively associated with the first axis, while DO and pH were negatively associated with the first axis. Temperature was negatively associated with the second axis, while canopy cover and calcium levels were positively associated with the second axis.

CCA axis 1 and 2 separated the sites into roughly three groups. The separation was based more on spatial than temporal variation; with samples from the same site generally being grouped closer to each other compared to those from other sites. The first group consisted of sites 4 and 6 that were affected by sewage effluent as well as site 5. These sites were positively associated with the first axis (Fig. 2). These sites were associated with high ammonium (which was positively correlated with turbidity, nitrite, phosphate, and manganese) and low pH and DO levels. Diatom species characterising these sites include species such as *Aulacoseira muzzanensis*, *Cyclotella ocellata*, *Gomphonema parvulum*, *G. gracile*, *G. pseudoaugur*, *Navicula gregalis,* and *Nitzschia palea.*

The second group consisted of Manyame River sites 7 and 8 that were negatively associated with the first and second axis. These sites were associated with high pH, temperature and DO and had low vegetation cover, conductivity, and nitrite levels. Diatom species characterising these sites include species such as *Aulacoseira granulata*, *Cymbella tumida*, *Cocconeis placentula*, *Eunotia formica*, *Encyonema perpusillum*, *Fragilaria pinnata*, *Fragilaria ulna*, *Gomphonema pumilum,* and *Navicula rhynchocephala*.

The third group consisted of sites 1, 2, and 3 that were positively associated with the second axis. These sites were associated with high vegetation cover and high calcium levels and had low

Table 1. The mean (n = 5) and standard deviation of physical and chemical variables recorded at all the sites during the study period (January to August 2012).

Variables	Sites							
	1	2	3	4	5	6	7	8
Water Temperature (°C)	19.8 ± 4.4	19.3 ± 4.5	20.9 ± 3.6	22.6 ± 3.1	21.1 ± 4.1	21.9 ± 3.8	23.3 ± 3.7	22.8 ± 4.6
Conductivity (µS.cm^{-1})	70.2 ± 15.6	68.0 ± 2.3	58.5 ± 3.5	85.0 ± 14.3	40.4 ± 6.9	68.2 ± 17.2	30.4 ± 2.3	31.0 ± 2.9
DO (mg.L^{-1})	6.1 ± 0.7	5.5 ± 0.7	6.0 ± 0.6	3.0 ± 0.8	5.4 ± 0.6	3.6 ± 1.1	7.1 ± 0.3	7.2 ± 0.5
pH	7.4 ± 0.2	7.3 ± 0.0	7.5 ± 0.2	7.0 ± 0.1	7.4 ± 0.1	7.1 ± 0.1	7.7 ± 0.1	7.8 ± 0.3
Turbidity (NTU)	3.5 ± 2.1	4.0 ± 1.8	2.7 ± 1.8	61.3 ± 17.7	2.2 ± 1.6	37.2 ± 6.7	1.5 ± 0.7	1.1 ± 0.3
Nitrite (mg.L^{-1})	0.9 ± 1.3	0.8 ± 1.5	0.5 ± 0.8	15.2 ± 8.1	0.8 ± 1.5	11.1 ± 6.6	0.5 ± 0.8	0.1 ± 0.1
Ammonium (mg.L^{-1})	0.4 ± 0.3	0.6 ± 0.3	1.0 ± 1.0	9.6 ± 8.2	2.6 ± 3.9	8.1 ± 8.3	1.9 ± 0.4	0.3 ± 0.2
Phosphate (mg.L^{-1})	< 0.1	< 0.1	0.3 ± 0.5	3.3 ± 5.8	0.1 ± 0.2	2.2 ± 2.6	0.3 ± 0.6	< 0.1
Calcium (mg.L^{-1})	9.1 ± 1.1	6.8 ± 1.3	5.8 ± 0.6	4.2 ± 2.0	3.9 ± 1.2	5.2 ± 1.2	4.3 ± 2.0	4.0 ± 4.2
Iron (mg.L^{-1})	0.03 ± 0.04	0.20 ± 0.20	0.01 ± 0.01	1.1 ± 0.56	0.1 ± 0.15	0.4 ± 0.37	0.20 ± 0.29	0.04±0.05
Manganese (mg.L^{-1})	0.13 ± 0.29	0.22 ± 0.40	< 0.02	1.04 ± 1.27	0.57 ± 1.04	0.51 ± 0.46	< 0.02	0.02±0.04
Canopy Cover (%)	60	90	75	15	45	55	5	10

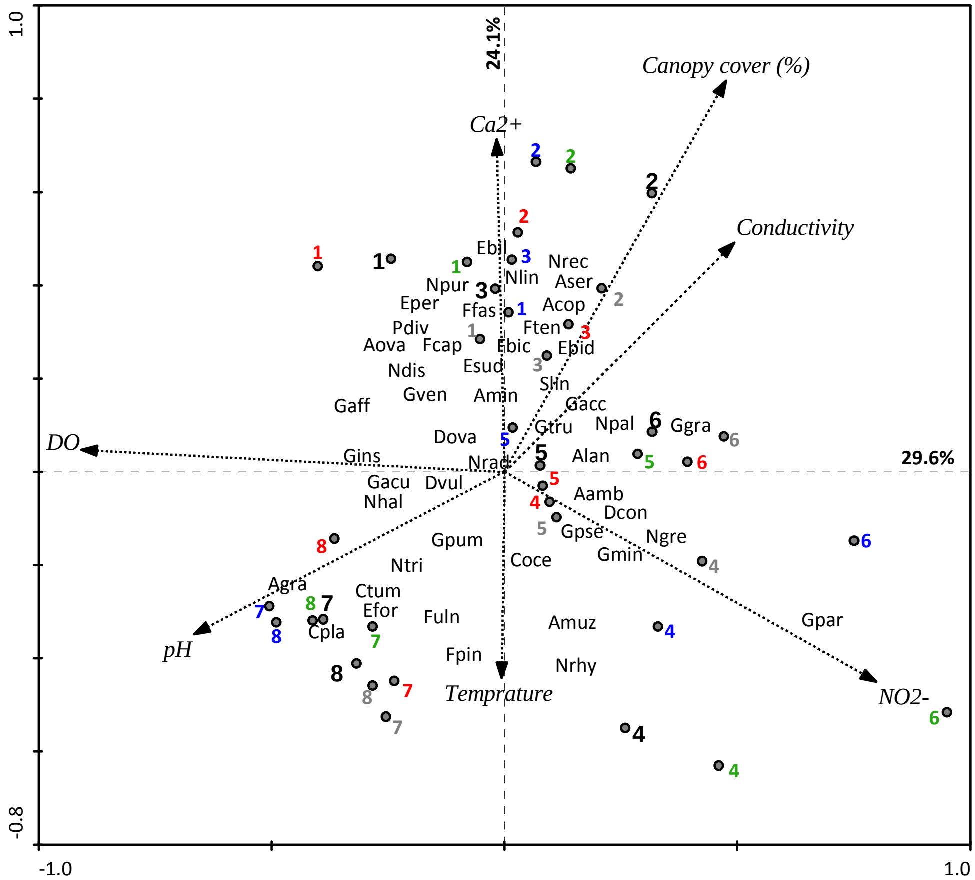

Fig. 2. CCA triplot showing the relationship between measured environmental variables and select diatom species (present in a minimum of two samples and had a relative abundance of ≥ 1 % in at least one sample) recorded at 8 sampling sites in streams draining Chinhoyi Town in January (gray), March (red), May (black), June (blue), and August (green) 2012. Site 3 was not sampled in August as it was dry. Species codes are presented in Table 2.

temperature and pH. Nutrient levels were generally low compared to those of sites 4 and 6 that were affected by sewage effluent. These sites were associated with such species as *Amphora copulata*, *Amphora ovalis*, *Eunotia bidentula*, *Eunotia bilunaris*, *Eunotia sudetica*, *Fragilaria fasciculata*, *Fragilaria tenera*, *Gomphonema affine*, *Gomphonema venusta*, *Navicula radiosa, Nitzschia dissipata*, *Nitzschia linearis*, *Nitzschia pura,* and *Surirella linearis*.

Discussion

On the basis of physical and chemical variables, pollution levels, especially eutrophication, differed among the sites sampled depending on sewage effluent discharge points in the catchment. Diatom community structure and composition closely followed the observed changes in pollution levels, with less polluted sites 7 and 8 being associated with diatom communities that were different from highly polluted sites 4, 5, and 6. Different diatom species in a community respond differently to changes in pollution because of differences in tolerances (Azim *et al*. 2005; Nautiyal *et al*. 2000; Pan *et al*. 1996; Potapova & Charles 2003; Patrick & Reimer 1966; Wehr & Sheath 2003). Therefore, the composition of diatom communities at different locations, or at different points in time, provide useful information about the environmental conditions. As pollution increased, low or moderate pollution tolerant species such as *C. tumida, C. placentula*, *E. formica,* and *E. perpusillum*, were replaced by high pollution tolerant species such as *A. muzzanensis, C. ocellata, G. parvulum, G. gracile, G. pseudoaugur, N. gregalis,* and *N. palea*. The former group of species consisted of cosmopolitan species found in oligo- to mesotrophic water with moderate conductivity (Bere 2014; Taylor *et al*. 2007b; Van Dam *et al*. 1994). On the other hand, the latter group of species have also been frequently recorded in waters that are nutrient rich and poorly oxygenated with high conductivity; variables that were retained in the CCA (Bere 2014; Bere & Tundisi 2009, 2010b, 2011a-e; Gómez & Licursi, 2001; Kobayasi & Mayama, 1989; Lobo *et al*. 2004; Van Dam *et al*. 1994). This group of species is known to be resistant to metal pollution (Bere & Tundisi 2012a-c; Duong *et al*. 2010).

Many studies describe *Nitzschia palea* (whose relative abundance was high at highly polluted sites) as cosmopolitan, high pollution tolerant species, especially to eutrophication (e.g., Kobayasi & Mayama 1989; Lange-Bertalot 1979; Lobo *et al*. 2002). The success of this species in eutrophic conditions has been attributed to obligate nitrogen heterotrophy, which is common in some *Nitzschia* species (Kilham *et al*. 1986). This in addition, would help them overcome the problem associated with low N : P ratios. This species as well as *Gomphonema parvulum* recorded at highly polluted sites, often become dominant in streams where treated sewage constitute the major component of the flow (Fukushima *et al*. 1994) or untreated sewage, as was the case in highly polluted sites. *Nitzschia palea* and *G. parvulum* have also been shown to be tolerant to metal pollution (Bere & Tundisi 2012 a-c, 2011f; Duong *et al*. 2010; Gold *et al*. 2003; Morin *et al*. 2008).

Studies carried out in rivers of Japan by Kobayasi & Mayama (1989) classified *G. parvulum* (whose relative abundance was high at highly polluted sites) as highly tolerant to eutrophication, which is in agreement with the results of this study. Similarly, Kelly *et al*. (1995), working in rivers of United Kingdom described this species as highly tolerant to eutrophication (indicative value = 3 and sensitivity value = 5) in their calculation of the Trophic Diatom index (TDI). *Gomphonema parvulum* has also been described as an indicator of high organic pollution, low concentrations of DO, and eutrophication (Lobo *et al*. 2002; Van Dam *et al*. 1994).

Perhaps the most relevant study to our study is that conducted by Gómez & Licursi (2001) on epipelic diatoms in the tropical streams of Argentina in an environment similar to this study. They classified 88 diatom species frequently found in the epipelion of Pampean streams and rivers based on ecological preferences according to water quality. Twenty of these species were among the most frequently occurring species in our study (Table 2): *A. minutisimum*, *A. lanceolata*, *A. granulata, A. ambigua, C. placentula, D. vulgaris, D. ovalis, E. bilunaris, E. sudetica, F. capucina*, *F. ulna, G. gracile*, *G. parvulum*, *G. pseudoaugur, G. truncatum, N. radiosa, N. rhynchocephala, N. linearis*, and *N. palea*. The distribution of all these species in relation to pollution was consistent with that described by Gómez & Licursi (2001).

Patrick & Reimer (1966) showed significant differences between diatom communities in calcareous and calcium-poor rivers. In this study, diatom communities at sites with high calcium levels (1, 2, and 3) differed from those at the rest of the sites. Calcium affects diatom motility and

Table 2. The relative abundance of the most abundant diatom species recorded at 8 sampling sites during the study period (January to August 2012). * = 0-10 %, ** = 10-30 %, *** = >30 %).

Species	Code	1	2	3	4	5	6	7	8
Achnanthes lanceolata Lange-bertalot	Alan	*	*	*	*	*	*	*	*
Achnanthidium minutissimum (Kützing) Czarnecki	Amin		*		*	*	*		
Amphora copulata (Kützing) Schoeman and Archbald	Acop	*		*					
Amphora ovalis (Kützing) Kützing	Aova	**	*	*		*	*	*	*
Anomoneis serians Cholnoky	Aser		*			*			
Aulacoseira ambigua (Grunow) Simonsen	Aamb	*			*	*	*	*	*
Aulacoseira granulata (Ehrenberg) Simonsen	Agra					*		**	*
Aulacoseira muzzanensis (Maister) Krammer	Amuz				*	*		*	
Cocconeis placentula Ehrenberg	Cpla	*			*	*		*	**
Cyclotella ocellata Pantocsek	Coce		*		*	*	*		*
Cymbella tumida (BrÉbisson) Van Heurck	Ctum	*	*	*	*	**	*	***	*
Diadesmis confervacea (Kützing) Mann	Dcon	*	*	*	*		*	*	*
Diatoma vulgaris Bory	Dvul			*			*	*	*
Diploneis ovalis (Hilse) Cleve	Dova			*				*	
Diploneis puella (Schumann) Cleve	Dpue	*		*				*	
Encyonema perpusillum (Cleve) Mann	Eper	*	*					*	*
Eunotia bidentula Smith	Ebid	*			*		*		
Eunotia bilunaris (Ehrenberg) Mills	Ebil	*	*					*	*
Eunotia formica Ehrenberg	Efor							*	*
Eunotia sudetica Müller	Esud	*	*			*			*
Fragilaria biceps (Kützing)	Fbic	*	**	**	**	*	*	*	*
Fragilaria capucina Desmaziéres	Fcap		**	**		*	*	*	*
Fragilaria fasciculata (Agardh) Lange-Bertalot	Ffas	*	*					*	
Fragilaria pinnata Ehrenberg	Fpin				*			*	
Fragilaria tenera (Smith) Lange-Bertalot	Ften	*		**		*	*	*	
Fragilaria ulna (Nitzsch) Lange-Bertalot	Fuln				*			*	
Gomphonema accuminatum Ehrenberg	Gacc	*					*	*	
Gomphonema gracile Ehrenberg	Ggra	*					*		
Gomphonema affine Kützing	Gaff	*							*
Gomphonema insigne Gregory	Gins	*	*					*	
Gomphonema minutum (Agardh) Agardh	Gmin	*			*	*	**		*
Gomphonema parvulum (Kützing) Cleve	Gpar	*		**	*	**	**	*	*
Gomphonema pseudoaugur Krammer	Gpse	*			*	*	*		
Gomphonema pumilum Reichardt and Lange-Bertalot	Gpum		*		*	*		*	*
Gomphonema truncatum Ehrenberg	Gtru	*				*			*
Gomphonema venusta Passy, Kociolek and Lowe	Gven	*		*		*			*
Gyrosigma acuminatum (Kützing) Rabenhorst	Gacu	*	*	*	*	*		*	*
Navicula gregalis Cholnoky	Ngre				**	*	*		
Navicula halophila (Grunow) Cleve	Nhal	*	*	*	*	*		*	*
Navicula radiosa Kützing	Nrad		*	*		*		*	
Navicula recens (Lange-Bertalot) Lange-Bertalot	Nrec		*			*			
Navicula rhynchocephala Kützing	Nrhy							*	*
Navicula tripunctata Müller Bory	Ntri		*				*	*	
Nitzschia dissipata (Kützing) Grunow	Ndis	*						*	
Nitzschia linearis (Agardh) Smith	Nlin	*	*	*	*			*	*
Nitzschia palea (Kützing) Smith	Npal	*	*	**	***	*	**	*	*
Nitzschia pura Hustedt	Npur	*	*						
Pinnularia divergens Krammer	Pdiv	*	*	*		*		*	*
Surirella linearis Smith	Slin	*	*		*	*	*	*	*

adhesion to surfaces (Cohn & Disparti 1994), but the exact physiological mechanisms responsible for the higher or lower affinity of diatoms to calcium are still unknown.

Vegetation cover, temperature, and pH were also found to be important in structuring benthic diatom communities in the study area. Vegetation cover has an attenuation effect on light intensity and penetration and hence photosynthesis (Potapova & Charles 2005). Temperature is an important driver of metabolic activities in benthic diatoms in lotic systems (Pan *et al.* 1996), while pH exerts a direct physiological stress on diatoms (Gensemer 1991; Round 2004), and also strongly influences other water chemistry variables (Stumm & Morgen 1981).

Conclusions

The autecological data presented in this study further contributes to our understanding of how diatoms are distributed in tropical lotic systems with respect to environmental variables. This is useful for the purposes of effective diatom-based water quality assessment and general assessment of ecological conditions of lotic systems and contributes to further understanding of the ecology of diatoms in tropical systems. Certain species like *A. muzzanensis, C. ocellata, G. parvulum, G. gracile, G. pseudoaugur, N. gregalis,* and *N. palea* associated with the pollution extremes may be used in future studies as potential indicator species for eutrophication. These species can be subjected to further experiments to confirm their status of indicator species. Further studies encompassing additional river systems (as opposed to the current study) with different environmental conditions are required to ascertain the behaviour of these species. Better coverage (more sites per area) would further improve the autecological information needed in the country for production of a sound diatom-based water quality assessment protocol as autecology of more diatom species could be quantified. Special attention also needs to be paid to diatom taxonomy, which was one of the major challenges in this study.

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