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RESEARCH ARTICLE

Challenges of diatom-based biological monitoring and assessment of streams in developing countries

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Abstract Stream biomonitoring tools are largely lacking for many developing countries, resulting in adoption of tools developed from other countries/regions. In many instances, however, the applicability of adopted tools to the new system has not been explicitly evaluated. The objective of this study was to test the applicability of foreign diatom-based water quality assessment indices to streams in Zimbabwe, with the view to highlight challenges being faced in diatom-based biological monitoring in this developing country. The study evaluated the relationship between measured water quality variables and diatom index scores and observed some degree of concordance between water quality variables and diatom index scores emphasising the importance of diatom indices in characterisation and monitoring of stream ecological conditions in developing countries. However, ecological requirements of some diatom species need to be clarified and incorporated in a diatom-based water quality assessment protocol unique to these regions. Resources should be channelled towards tackling challenges associated with diatom-based biological monitoring, principally taxonomic studies, training of skilled labour and acquiring and maintaining the necessary infrastructure. Meanwhile, simpler coarse taxonomy-based rapid bioassessment protocol, which is less time and resource consuming and requires less specialised manpower, can be developed for the country.

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Introduction

River health monitoring and assessment is increasingly becoming important because of the anthropogenic activities that have significantly affected the water quality of aquatic systems. Diatoms have been used extensively in river health assessment programmes, especially in developed countries (Slàdeček 1986; Watanabe et al. 1986; Leclerq and Maquet 1987; Descy and Coste 1991; Kelly and Whitton 1995; Prygiel et al. 1996; Rott et al. 1997, 1999; Lobo et al. 2004; Lavoie et al. 2008). They respond rapidly to degradation of water quality, and the integrity of these communities provides a direct, holistic and integrated measure of river ecosystem health. They have gained momentum in their usage as alternatives to chemical analyses because the latter techniques provide, at best, a fragmented overview of the state of river systems as sporadic or periodic sampling cannot reflect fluxes of effluent discharge typical of real-world experiences. Diatom-based monitoring tools are particularly essential for the management of rivers in developing countries as they are fast and cost-effective approaches for assessing the effects of environmental stressors (McCormick and Cairns 1994; Taylor et al. 2007a; Harding et al. 2015; Bere and Tundisi 2010). Several diatom-based river health assessment indices have been developed, most of which are general pollution indices, especially indicative of eutrophication and organic pollution. These indices are thought to have universal applicability across geographic areas and environments because of the cosmopolitan nature of most diatom species (McCormick and Cairns 1994; Harding et al. 2015). Thus, due to lack of information on ecological preferences and tolerances of diatoms in developing countries, indices developed in developed countries are often borrowed.

There is, however, evidence that diatom indices developed in one geographic area or environment are less successful when applied in other areas (Pipp 2002). This is due to the floristic differences among regions (Taylor et al. 2007a) and the environmental differences that modify species responses to water quality characteristics (Potapova and Charles 2007). Strict testing of these borrowed indices is required to ensure that diatom index scores give a realistic reflection of the specific type of environmental pollution being tested.

Attempts to use diatoms as indicators of water quality changes are fairly recent and have relatively few precedents 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. They 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. Recent studies have also demonstrated the robust and quantifiable nature of the relationship between diatoms and environmental variables indicating the potential use of diatoms as ecological indicators in the country (Bere et al. 2013; Bere et al. 2014; Mangadze et al. 2015). Besides this study, diatom communities and their ecological requirements have largely been unexplored in the study region, hampering the use of diatoms as ecological indicators.

The objective of this study was to test the applicability of foreign diatom-based water quality assessment indices to streams in Zimbabwe, with the view to highlight challenges being faced in diatom-based biological monitoring in developing countries. In Zimbabwe, the potential for using diatoms as bioassessment tools has not been fully realised and benthic diatoms have not been widely used in state water quality assessment programs. The applicability of the diatom indices developed in other regions and calculated by the OMNIDIA version 5.3 software was tested in two ecological settings: (1) streams draining urban areas (Chinhoyi, Zimbabwe) and (2) relatively pristine streams draining the protected Nyanga National Park in the Eastern Highlands of Zimbabwe.

Materials and methods

Study area

The study was carried out in two ecological settings: (1) streams draining urban areas (Chinhoyi, Zimbabwe) and (2) relatively pristine streams draining the protected Nyanga National Park in the Eastern Highlands of Zimbabwe (Fig. 1). In the first ecological setting, the study streams passed through Chinhoyi city. The area has average annual temperature of around 24.5 °C, with a mean monthly maximum of 29.9 °C recorded in October and November and a mean monthly minimum of 18.9 °C recorded in July. In 2012, the population of Chinhoyi was estimated at 79 368 inhabitants by the Zimbabwe National Statistics Agency (ZNSA). The expansion of the city does not meet the technical standards that go with it in terms of sewage treatment, collection of garbage, urban drainage and so on. Streams in the study area, therefore, receive untreated or semi-treated effluent from various domestic and industrial sources as well as other diffuse sources as they pass through the city. This disorderly growth of the city, typical of most developing countries, results in stream health deterioration especially due to organic pollution and eutrophication. A total of eight sites were established along streams in Chinhoyi. The criterion for selecting sampling sites was to enable evaluation of the impact of breakdown in municipal service delivery (especially sewage treatment) on water quality and the associated diatom communities in the study streams. Site 1 was located downstream on the Manyame River, while site 6 was located upstream on the same river, in a relatively less-polluted area. Large flow volumes in the Manyame River (the upper reaches of which drain less polluted commercial farms) are expected to have a dilution effect on pollutants at sites 1 and 6. Sites 2, 5, and 7 were located just after sewage effluent discharge points. Sites 3, 4, and 8 were located in the town centre where uncollected garbage and effluent from broken sewage pipes finds its way into the stream. All of the sites were sampled four times on the following dates: 04 March 2012, 16 May 2012, 30 July 2012 and 27 August 2012.

In the second ecological setting, headwaters of the study streams fall within the protected Nyanga National Park (Fig. 1). As the rivers leave the park, they flow into low-lying relatively pristine sparsely populated areas characterised by plantations and rural communities with highly preserved riparian buffer zones. Mean annual temperature of lower lying areas range from 17.5 to 20 °C as compared to 15 °C for higher altitude areas. A total of 21 sites were established in the study area (Fig. 1). Diatom and water quality sampling were recorded once off at 21 sites between May and August 2007. Along the Nyangombe River, sites N1 to N6 were located in protected areas while sites N6 to N9 were located in unprotected areas. Along the Pungwe River, sites P1 to P5 were located in protected areas while sites P6 and P7 were located in unprotected areas. All the five sites sampled along the Kairezi River were located in unprotected areas except K3, which was located in communal area management program for indigenous resources (CAMPFIRE), a semi-protected area.

In all the ecological settings, sampling was done during the stable flow periods to avoid variable effects of rainy season such as great variations in water level and velocity, floods and inundations, which are known to affect diatom development, especially growth rate and relative abundance of different

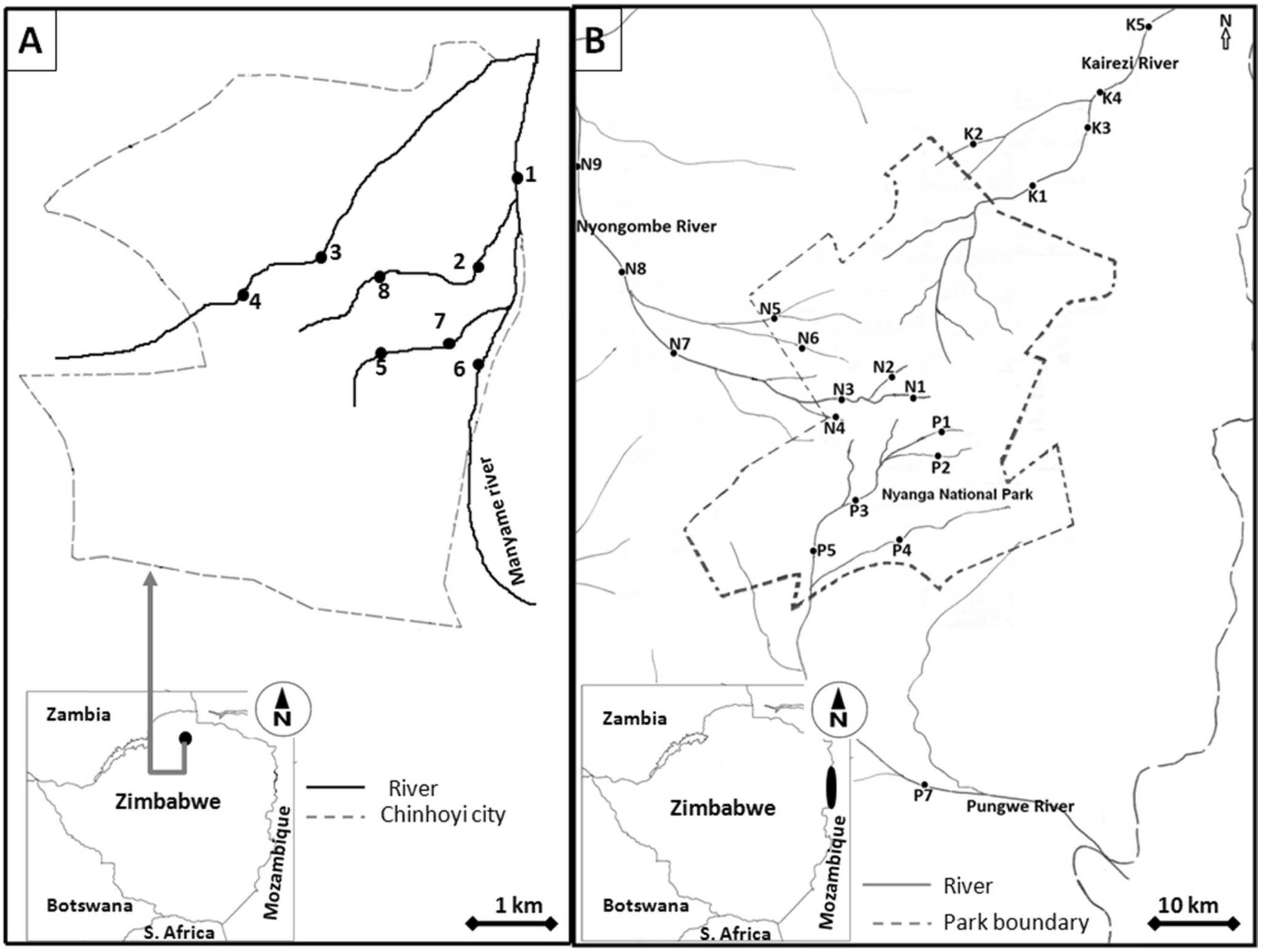

Fig. 1 Location of **a** Chinhoyi and **b** the Eastern Highlands of Zimbabwe and sampling stations in these study areas

species (Round 1991). More detailed descriptions of the study areas can be found in Bere and Tundisi (2011), Bere et al. (2013) and Bere et al. (2014).

Environmental variables

In Chinhoyi, temperature, pH and electrical conductivity were measured with ERMA meters (ERMA Inc. Japan). Dissolved oxygen (DO) was measured with a Bante 820 meter (Bante, China). Turbidity, nitrate (NO_3^-) and phosphate (PO_4^{3-}) were measured with Hach DR/2010. In the Eastern Highlands, temperature, pH, electrical conductivity, dissolved oxygen, turbidity and nitrate (NO_3^-) were measured using Horiba U-23 and W-23XD Water Quality meter (Horiba Ltd., Japan).

Biological elements

At all the sites, epilithic diatom samples were sampled by brushing stones with a toothbrush. Dead wood was used as a substrate in the absence of boulders at two sites as suggested by Kelly and Whitton (1995). 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. In the laboratory, sub-samples 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 and Kilroy (2000). Three replicate slides were prepared for each sample. Around 400 valves per sample (based on counting efficiency determination method by Pappas and 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 on the following studies: Metzeltin et al. (2005), Bicudo and Menezes

(2006), Taylor et al. (2007c) and Metzeltin and Lange-Bertalot (1998, 2007).

Indices and data analysis

The diatom species counts were entered into the diatom database and index calculation tool OMNIDIA version 5.3 (Lecointe et al. 1993). Seventeen indices were calculated and tested (Table 1). For full data analysis, results and discussion of benthic diatom communities in relation to environmental variables in the study area, refer to Bere et al. (2013) and Bere et al. (2014). Pearson's correlation (performed using Palaeontological Statistics (PAST) software version 2.16; Hammer et al. 2009) was used to determine the relationship between the calculated index scores and measured physical and chemical water quality data.

Results

Environmental variables

The values of physical and chemical variables measured in these studies are shown in Table 2. Pollution levels were generally high in the sites draining Chinhoyi urban area. Temperature and pH were comparable among sites, though the later tended to be generally low at sites 2 and 7 that were affected by sewage effluent compared to the rest of the sites. Conductivity was relatively lower at sites 1 and 6 where large flow volumes of 'clean water' had a dilution effects on pollutants compared to the rest of the sites. Turbidity, nitrite and phosphate levels were relatively higher at sites 2 and 7 that were affected by sewage effluent compared to the rest of the sites, while DO was relatively lower at sites 2 and 7 compared to the rest of the sites. On the other hand, most of the sites in the Eastern Highlands of Zimbabwe were pristine, especially those within the Nyanga National Park.

Indices

Diatom community structure and composition in the two ecological settings generally tended to reflect pollution gradients. In the Eastern Highlands of Zimbabwe, a total of 119 diatom species belonging to 38 genera were recorded in 21 diatom samples collected. Diatom communities characterising these samples included low to medium pollution tolerant taxa such as *Cocconeis placentula*, *Cymbella javanica*, *Cymbella perpusilla*, *Cymbella tumida*, *Cymbella kappii*, *Cymatopleura solea*, *Hantzschia amphioxys*, *Navicula theronii*, *Eunotia fallax*, *Navicula rhynchocephala* and *Placoneis dicephala*. In streams draining Chinhoyi urban area, 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; hence, species distribution was strongly biased towards those that are cosmopolitan and tolerant of elevated or slightly elevated levels of pollution. Diatom species characterising these sites include species such as

Table 1 List of diatom indices for water pollution monitoring calculated in this study

Index name	Index abbreviation	Eutrophication/organic load or water quality rates	Reference
Saprobity index (Sládeček's index)	SLA	0 (best) to 4 (worse)	Slàdeček 1986
Descy's pollution index	DES	1 (worse) to 5 (best)	Descy 1979
Leclercq and Maquet's index	LMI	1 (worse) to 5 (best)	Leclerq and Maquet 1987
Schiefele and Schreiner's index	SHE	1 (worse) to 7 (best)	Schiefele and Schreiner 1991
Watanabe index	WAT	0 (worse) to 100 (best)	Watanabe et al. 1986
Trophic diatom index	TDI	0 (best) to 100 (worse)	Kelly and Whitton 1995
Generic diatom index	GDI	0 (best) to 100 (worse)	Coste and Ayphassorho 1991
Commission for Economical Community index	CEC	0 (worse) to 10 (best)	Descy and Coste 1991
Specific pollution sensitivity index	SPI	1 (worse) to 5 (best)	CEMAGREF 1982
Biological diatom index	BDI	1 (worse) to 7 (best)	Lenoir and Coste 1996
Artoise-Picardie diatom index	APDI	1 (worse) to 5 (best)	Prygiel et al. 1996
Eutrophication/pollution index	EPI-D	0 (best) to 4 (worse)	Dell'Uomo 1996
Swiss Diatom Index	DI-CH	1 (best) to 8 (worse)	BUWAL 2002
Pampean Diatom Index	PDI	0 (best) to 4 (worse)	Gómez and Licursi 2001
Biological water quality index	BWQI	1 (best) to 4 (worse)	Lobo et al. 2004
Saprobic index	SI	1 (best) to 3.8 (worse)	Rott et al. 1997
Trophic index	TI	0.3 (best) to 3.9 (worse)	Rott et al. 1999

Table 2 The mean of physical and chemical variables recorded in the three study areas during the different study periods

		Temperature (°C)	DO (mg l^{-1})	Conductivity (μS cm^{-1})	pH	Turbidity (NTU)	NO_3^- (μg l^{-1})	PO_4^{3-} (μg l^{-1})
Chinhoyi	1	22.8	7.2	31.0	7.8	1.1	10.0	<2
	6	23.3	7.1	30.4	7.7	1.5	50.0	3.0
	8	20.9	6.0	58.5	7.5	2.7	50.0	3.0
	3	19.3	5.5	68.0	7.3	4	80.0	<2
	4	19.8	6.1	70.2	7.4	3.5	90.0	<2
	5	21.1	5.4	40.4	7.4	2.2	80.0	100.0
	7	21.9	3.6	68.2	7.1	37.2	111.0	220.0
	2	22.6	3.0	85.0	7.0	61.3	152.0	330.0
Eastern Highlands	1	13.7	6.0	29.0	6.5	1.5	1.1	[a]
	2	15.1	6.6	29.0	6.3	1.5	7.1	[a]
	3	13.7	7.2	39.0	7.2	2.3	8.8	[a]
	4	13.6	7.0	49.0	6.5	2.2	10.9	[a]
	5	13.0	7.5	76.0	7.0	3.8	23.3	[a]
	6	13.9	7.0	29.0	7.2	1.5	11.4	[a]
	7	18.5	6.9	78.0	6.5	3.7	14.8	[a]
	8	19.1	7.2	73.0	6.9	3.8	11.1	[a]
	9	19.1	7.4	76.0	7.0	3.7	13.8	[a]
	10	14.3	7.0	29.0	7.1	1.5	7.3	[a]
	11	14.4	6.8	21.0	6.8	0.6	5.7	[a]
	12	14.1	7.7	23.0	6.6	0.7	6.0	[a]
	13	14.8	7.0	16.0	6.4	0. 5	7.1	[a]
	14	15.7	7.4	20.0	6.7	0.8	7.7	[a]
	15	19.0	7.2	27.0	6.6	1.5	7.7	[a]
	16	18.6	7.3	30.0	6.8	1.5	10.5	[a]
	17	12.3	7.2	43.0	6.7	2.2	14.1	[a]
	18	11.1	7.9	40.0	6.8	2.3	13.8	[a]
	19	13.7	7.9	35.0	6.5	1.5	8.8	[a]
	20	15.6	7.5	25.0	7.3	1.5	11.5	[a]
	21	16.5	7.8	29.0	6.9	1.5	9.4	[a]

[a] Not measured

Aulacoseira muzzanensis, *Cyclotella ocellata*, *Gomphonema parvulum*, *Gomphonema gracile*, *Gomphonema pseudoaugur*, *Navicula gregalis*, and *Nitzschia palea*. The distribution of most frequently occurring diatom taxa in Chinhoyi and the Eastern Highlands of Zimbabwe is shown in Appendix 1. Detailed, results and discussion of benthic diatom communities in relation to environmental variables in these two study areas can be found in Bere et al. (2013) and Bere et al. (2014).

A total of 25 and 43 % of the diatom species were not entered into OMNIDIA for calculation of indices in Chinhoyi and the Eastern Highlands, respectively. Significant correlations ($p<0.05$) were generally observed between most of the index scores and water quality variables, especially in highly polluted urban areas (Table 3). The correlations were significantly low ($p<0.05$) for Eastern Highlands compared to Chinhoyi urban sites. Indices such as the saprobity index (SLA), Leclercq and Maquet's index (LMI) by Leclerq and Maquet (1987, see Table 1), Generic diatom index (GDI) and Artoise-Picardie diatom index (APDI) were not significantly correlated with any of the measured environmental variables in the Eastern Highlands.

Discussion

The two case studies provide abundant evidence that epilithic diatom communities are good reflectors of human-induced degradation of water quality in tropical streams as evidenced by observed correlations between some diatom index scores and some environmental variables in the study regions. This indicates the importance of foreign diatom indices in assessing anthropogenic changes in water quality in the study regions as

Table 3 Pearson correlation coefficients between measured environmental variables and diatom index scores generated for sites in the Chinhoyi and Eastern Highlands rivers

		SLA	DES	LMI	SHE	WAT	TDI	GDI	CEE	SPI	BDI	APDI	EPI	DI-CH	PDI	BIWQ	SI	TI
Chinhoyi	Temperature	0.64	–	−0.52	–	–	0.56	–	–	–	−0.49	–	0.71	–	–	–	–	–
	DO	−0.71	0.93	0.8	0.93	0.85	−0.56	0.87	0.51	0.92	0.81	–	−0.39	−0.84	−0.89	−0.88	−0.86	−0.86
	Conductivity	–	−0.52	–	−0.52	−0.86	–	−0.93	–	−0.53	–	–	–	–	0.48	0.60	0.48	0.42
	pH	–	0.66	–	0.65	0.95	–	0.93	0.47	0.65	–	–	–	−0.58	−0.61	−0.76	−0.70	−0.56
	Turbidity	0.84	−0.93	−0.85	−0.82	−0.65	0.65	−0.77	−0.40	−0.94	−0.84	–	0.60	0.77	0.84	0.83	0.80	0.88
	NO_2^-	0.82	−0.95	−0.89	−0.87	−0.63	0.72	−0.73	–	−0.96	−0.90	–	0.59	0.81	0.90	0.81	0.82	0.92
	PO_4^{3-}	0.88	−0.92	−0.85	−0.80	−0.62	0.64	−0.74	–	−0.94	−0.84	–	0.62	0.76	0.81	0.84	0.77	0.86
Eastern Highlands	Temperature																	
	DO	–	0.67	–	–	–	–	–	–	–	–	–	0.70	–	–	–	–	–
	Conductivity	–	–	–	–	–	−0.77	–	–	0.5	–	–	0.83	0.64	0.78	–	–	–
	pH	–	−0.63	–	–	–	–	–	–	–	−0.6	–	–	–	–	−0.52	−0.63	–
	Turbidity	–	–	–	0.57	–	−0.53	–	0.48	0.61	−0.66	–	0.61	–	0.66	–	–	–
	NO_2^-	–	–	–	–	–	−0.57	–	–	–	−0.76	–	0.73	0.53	0.87	–	–	−0.52
	PO_4^{3-}	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Numerical values indicate significant correlations at $p \leq 0.05$. Index abbreviations correspond to those in Table 2

*Not measured

recorded elsewhere (Prygiel and Coste 1993; Kwandrans et al. 1998; Taylor et al. 2007a, b). Although concerns have been raised as to the feasibility of transferring data concerning the ecological tolerance limits of diatoms among regions (Round 1991), most of the dominant diatom species encountered in these studies (detailed in Bere et al. (2013) and Bere et al. (2014)) are cosmopolitan species well-documented in international literature (e.g. Krammer and Lange-Bertalot 1986–1991). For that reason, most foreign diatom indices may be used in the study regions, especially in eutrophic, organically enriched waters, as they are based on the ecology of widely distributed or cosmopolitan taxa. Thus, diatom-based biotic indices constitute appropriate technical tools for environmental monitoring programs and water quality assessment in tropical streams. These techniques are particularly essential for stream monitoring and assessment in developing countries as they are fast and cost-effective approaches for assessing the effects of environmental stressors (McCormick and Cairns 1994; Taylor et al. 2007a; Harding et al. 2015; Bere and Tundisi 2010).

In highly polluted Chinhoyi urban area, the correlation coefficients were better than the correlations demonstrated in Europe and South Africa. Diatom-based biomonitoring techniques were born in the wake of the Industrial Revolution and urbanisation to measure the effects of environmental stressors, especially eutrophication and organic pollution, on aquatic systems. Thus, most of the indices are general pollution indices, especially indicative of eutrophication and organic pollution, hence their better reflection of water quality in eutrophication/organic pollution-prone streams draining urban industrialised areas.

On the other hand, in relatively pristine waters of the Eastern Highlands of Zimbabwe, correlations between index scores and water quality variables were general week and indices such as the SLA, LMI, Watanabe index (WAT), GDI and APDI were not significantly correlated to all the water quality variables (Table 3). This was not the case in studies carried out in eutrophic waters in Chinhoyi as well as from other regions (Kwandrans et al. 1998; Taylor et al. 2007a, b; Bere and Tundisi 2011). This highlights the limitations of the current diatom-based biotic indices in assessing water quality in relatively pristine environments.

In addition, cosmopolitan genera such as *Navicula*, *Nitzschia*, and *Gomphonema* with a wide range of tolerances to various water quality variables were among the dominant species in these studies (Bere and Tundisi 2011; Bere et al. 2013, 2014). Environmental optima and tolerance ranges of these ‘cosmopolitan’ species may vary in tropical regions (Lobo et al. 2004) affecting the correlation of temperate-based diatom index scores with water quality parameters. Thus, their use in calculation of indices may not always yield consistent results (Gómez and Licursi 2001). In addition, the hypothesis of cosmopolitanism of microorganisms (Finlay et al. 2002), one of the reasons given for universal applicability of diatom indices across geographic areas, is now a subject of much debate. For example, recent evidence suggest that certain species, originally believed to have a cosmopolitan distribution such as *N. palea* and *G. parvulum*, exhibit biogeographical or phylogeographical pattern of distribution, probably not supporting the hypothesis that only the environment selects (Trobajo et al. 2009; Boo et al. 2010; Kermarrec et al. 2013; Abarca et al. 2014). Separate taxa exist within these species complexes among geographic regions (Kermarrec et al. 2013; Abarca et al. 2014), which may not all share the same environmental optima and tolerances, hence discrepancies in the correlations between the calculated index scores and water quality variables. These taxa are currently being lumped in the calculation of most of the diatom indices. Round (2004) discovered that lumping of several similar looking taxa into one 'morphospecies' diminishes discriminative ability of diatom indices. Better predictive capacity of diatom-based assessment models has been shown with finer taxonomic resolutions than that with coarser ones (Rimet and Bouchez 2012). Thus, detailed taxonomic and ecological studies are required to fine tune diatom indices for water quality assessment.

However, Rimet and Bouchez (2012) showed that taxonomic resolution has little influence on diatom assemblage structure description, with little ecological information being lost when resolution is decreased from species to order level. This has also been observed with other biotic indicators such as freshwater benthic macroinvertebrates (Bowman and Bailey 1997; Metzeling et al. 2006). Though information content increases with taxonomic resolution, taxonomic identifications have been shown to become less certain at finer resolutions (Jones 2008) and data noise has also been shown to increase with increasing taxonomic resolution (Bowman and Bailey 1997). Identification to species level in this study has been difficult. The taxonomic challenges faced in this study can partially mask the diatom assemblage environmental relationships (Rimet and Bouchez 2012), hence affecting the sensitivity of indices. For this reason, ecological assessments using diatoms are less common than those using macroinvertebrates in Zimbabwe, with the majority of diatom indices being based on species or sub-species levels (Rimet 2012) and requiring highly qualified staff and resources currently lacking in the country. One way of circumventing taxonomic resolution challenges faced in this study is to resort to coarse taxonomy, which is also fair easy, less time and resource consuming and require less specialised manpower, with care being taken to ensure that not much ecological information is lost when resolution is decreased as this may compromise model inference. Indeed, several studies have shown good results with coarse diatom taxonomy in rapid bioassessment of ecological quality in freshwater systems (e.g. Growns 1999; Hill et al. 2001; Wunsam et al. 2002; Raunio and Soininen 2007). The recent demonstration of existence of a phylogenetic signal for ecological traits at lower taxonomic resolution (Keck et al. 2015) is promising for the development of simpler coarse taxonomy-based rapid bioassessment protocols.

Several common and abundant taxa (25 and 43 % in Chinhoyi and the Eastern Highlands, respectively), were not taken into account during index calculation, and this may lead to erroneous results. There were also a large number of unidentified taxa, especially in the Eastern Highlands, that require further taxonomic work. The ecological preferences of these diatoms species have yet to be determined, with some probably being endemic to these regions, rendering them useless in the calculation of index scores using OMNIDIA. Incorporation of these taxa in index calculation may give a better picture of the investigated water. In addition, some of the indices, such as SLA and WAT, have been developed three or four decades ago and have never been updated in keeping with highly dynamic diatom taxonomy.

Conclusion

Foreign indices are generally applicable to the study regions, especially in urban settings, because many widely distributed diatom species have similar environmental tolerances to those recorded for these species elsewhere, but there are several issues to be considered. There is need for taxonomic clarification (major challenge of the present study) and research on ecological requirements of some diatom species in the study region. When these undescribed taxa are abundant, as in the case of the Eastern Highlands of Zimbabwe, water quality may be misinterpreted. Meanwhile, a simpler coarse taxonomy-based rapid bioassessment protocol, which is less time and resource consuming and require less specialised manpower, can be developed for the country.

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Appendix 1

Table 4 The distribution of most frequently occurring diatom taxa in Chinhoyi (CH) and the Eastern Highlands of Zimbabwe (EH)

Species	CH	EH	Species	CH	EH
Achnanthes linearoides Lange-Bertalot		*	*Gomphonema minutum* (Agardh) Agardh	*	*
Achnanthidium cf minutissimum	*	*	*Gomphonema parvulum* (Kützing) Kützing	*	*
Achnanthidium exiguum (Grunow) Czarnecki		*	*Gomphonema pseudoaugur* Krammer	*	
Amphora copulata (Kützing) Schoeman and Archibald	*		*Gomphonema pumilum* Reichardt & Lange-Bertalot	*	
Amphora ovalis (Kützing) Kützing	*		*Gomphonema* sp. 1		*
Anomoeoneis sp.		*	*Gomphonema* sp. 2		*
Aulacoseira ambigua (Grunow) Simonsen	*		*Gomphonema* sp. 3		*
Aulacoseira granulata (Ehrenberg) Simonsen	*		*Gomphonema* sp. 4		*
Aulacoseira muzzanensis (Meister) Krammer	*		*Gomphonema* sp. 5		*
Brachysira serians (Brébisson) Round & DG Mann	*		*Gomphonema venusta* Passy, Kociolek & Lowe	*	
Caloneis bacillum (Grunow) Cleve		*	*Gomphonema truncatum* Ehrenberg	*	
Caloneis hyalina Hustedt	*	*	*Gyrosigma acuminatum* (Kützing) Rabenhorst	*	*
Caloneis sp.		*	*Gyrosigma attenuatum* (Kützing) Cleve		*
Cocconeis pediculus Ehrenberg		*	*Hantzschia amphioxys* (Ehrenberg) Grunow	*	*
Cocconeis placentula Ehrenberg	*	*	*Melosira* sp.		*
Cocconeis sp.		*	*Melosira varians* Agardh		*
Cyclotella sp.		*	*Navicula recens* (Lange-Bertalot) Lange-Bertalot	*	
Cyclotella meneghiniana Kützing	*	*	*Navicula capitatoradiata* Germain		*
Cyclotella ocellata Pantocsek	*		*Navicula cryptocephala* (Grunow) Cleve	*	*
Cymatopleura solea (Brébisson) Smith	*	*	*Navicula cryptotenella* Lange-Bertalot		*
Cymbella aspera (Ehrenberg) Peragallo		*	*Navicula gregalis* Cholnoky	*	
Cymbella chasei Cholnoky		*	*Navicula halophila* (Grunow) Cleve	*	
Cymbella javanica Hustedt		*	*Navicula microcephala* Grunow		*
Cymbella kappii (Cholnoky) Cholnoky		*	*Navicula radiosa* Kützing	*	*
Cymbella perpusilla Cleve		*	*Navicula rhynchocephala* Kützing	*	*
Cymbella sp. 1		*	*Navicula rostellata* Kützing		*
Cymbella sp. 2		*	*Navicula* sp. 1		*
Cymbella sp. 3		*	*Navicula* sp. 2		*
Cymbella tumida (Brébisson) Van Heurck	*	*	*Navicula* sp. 3		*
Cymbopleura naviculiformis (Auerswald) Krammer		*	*Navicula* sp. 4		*
Diatoma sp. 1		*	*Navicula theronii* Cholnoky		*
Diatoma sp. 2		*	*Navicula tripunctata* Müller Bory	*	
Diatoma vulgaris Bory	*	*	*Neidium affine* (Ehrenberg) Pfitzer		*
Diploneis ovalis (Hilse) Cleve	*		*Nitzschia* sp. 1		*
Diploneis puella (Schumann) Cleve	*		*Nitzschia dissipata* (Kützing) Grunow	*	*
Encyonema mesianum (Cholnoky) DG Mann		*	*Nitzschia intermedia* Hantzsch		*
Encyonema neogracile Krammer		*	*Nitzschia linearis* (Agardh) Smith	*	*
Encyonema perpusillum (Cleve) Mann	*		*Nitzschia palea* (Kützing) Smith	*	*
Epithemia sorex Kützing		*	*Nitzschia pura* Hustedt	*	
Epithemia zebra (Ehrenberg) Kützing		*	*Nitzschia* sp. 2		*
Eunotia bidentula Smith	*		*Nitzschia* sp. 3		*
Eunotia bilunaris (Ehrenberg) Mills	*	*	*Nitzschia* sp. 4		*
Eunotia fallax Cleve		*	*Nupela praecipua* (Reichardt) eichardt		*
Eunotia formica Ehrenberg	*		*Nupela* sp.		*
Eunotia minor (Kützing) Grunow		*	*Pinnularia divergens* Krammer	*	
Eunotia pectinalis (Ralfs) Rabenhorst		*	*Pinnularia* sp.		*
Eunotia sp. 1		*	*Pinnularia viridis* (Nitzsch) Ehrenberg	*	*

Table 4 (continued)

Species	CH	EH	Species	CH	EH
Eunotia sp. 2		*	*Placoneis dicephala* (Smith) Mereschkowsky		*
Eunotia sp. 3		*	*Placoneis* sp.		*
Eunotia sp. 4		*	*Planothidium lanceolatum* (Brébisson) Grunow	*	
Eunotia sp. 5		*	*Reimeria sinuata* (Gregory) Kociolek & Stoermer		*
Eunotia sp. 6		*	*Rhopalodia gibba* (Ehrenberg) Müller		*
Eunotia sudetica Müller	*		*Stauroneis anceps* Ehrenberg		*
Fragilaria pinnata Ehrenberg	*		*Stauroneis* sp.		*
Fragilaria biceps (Kützing)	*		*Staurosira construens* Ehrenberg		*
Fragilaria capucina Desmazières	*	*	*Stenopterobia delicatissima* (Lewis) Brébisson		*
Fragilaria sp.		*	*Stenopterobia* sp.		*
Fragilaria tenera (Smith) Lange-Bertalot	*		*Surirella linearis* Smith	*	*
Frustulia rhomboides (Brebisson) Ross		*	*Surirella robusta* Ehrenberg		*
Frustulia vulgaris (Thwaites) De Toni	*	*	*Surirella* sp.		*
Gomphonema accuminatum Ehrenberg	*	*	*Surirella tenera* Gregory	*	*
Gomphonema affine Kützing	*		*Synedra capitata* Ehrenberg		*
Gomphonema angustatum (Kützing) Rabenhorst		*	*Tabellaria flocculosa* (Roth) Kützing		*
Gomphonema gracile Ehrenberg	*		*Tabularia fasciculata* (Agardh) Williams & Round	*	
Gomphonema insigne Gregory	*		*Ulnaria ulna* (Kützing) Compère	*	*

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