Hydrobiologia (2007) 592:455–464
DOI 10.1007/s10750-007-0788-1

PRIMARY RESEARCH PAPER

Can diatom-based pollution indices be used for biomonitoring in South Africa? A case study of the Crocodile West and Marico water management area

Jonathan Charles Taylor · Jean Prygiel · Andre Vosloo · Pieter A. de la Rey · Leon van Rensburg

Received: 14 August 2006 / Revised: 2 May 2007 / Accepted: 17 May 2007 / Published online: 31 July 2007

Abstract The inclusion of diatoms into the current suite of biomonitoring tools in use in South Africa, as well as the use of European and other diatom indices in South Africa, and in particular the Crocodile and West Marico water management area, is discussed. The indices, when compared to chemical analyses, proved useful in providing an indication of the quality of the investigated waters. Several widely distributed diatom species were shown to have similar ecological tolerances in South Africa when compared to Europe. Although most of the diatoms encountered in the study were cosmopolitan, several possibly endemic species were recorded. The occurrence of endemic species, not included in existing diatom indices may lead to miscalculations of diatom indices. It is concluded that although diatom indices developed in Europe and elsewhere are useful at the present to indicate water quality, a diatom index unique to South Africa including endemic species will have to be formulated.

Keywords Diatoms · Indices · Water quality · Biomonitoring

Handling editor: D. Hamilton

J. C. Taylor (✉) · A. Vosloo · P. A. de la Rey · L. van Rensburg
School of Environmental Sciences and Development, North-West University, Potchefstroom Campus, Private Bag X6001, Potchefstroom 2520, South Africa
e-mail: Jonathan.Taylor@nwu.ac.za

J. Prygiel
Mission Ecologie du Milieu, Agence de l'Eau Artois-Picardie, 200 rue Marceline, 59508 Douai Cedex, France

Introduction

Water resources in South Africa are scarce, often naturally ephemeral and are difficult to manage. Large volumes of water are transferred from both inside and outside of South Africa to supply the steadily growing demands of industrial and urban centres. Together with the increased demand on use of South Africa's water resources, comes the eventual return of effluent water (usually after some form of ameliorative treatment) to rivers, streams and impoundments. Effluent returns and diffuse discharges (e.g. runoff from agricultural land) may significantly alter the natural state of receiving water bodies by the addition of chemical compounds, colloidal material and suspended solids, often resulting in changes in salinity, nutrient status and turbidity. These changes will in turn alter the structure of aquatic communities to a larger or smaller extent.

Chemical and physical changes in water bodies around South Africa are monitored by the Department of Water Affairs and Forestry

(DWAF) and part of the National Chemical Monitoring Programme. However, as with many chemical monitoring programmes, it is simply too expensive to monitor resources at the spatial and temporal frequency required to develop an accurate reflection of the true state of the water body in question. A chemical sample of water quality in essence provides a single ‘‘snapshot’’ bound to a certain brief time when the sample was collected. In addition, no information is gained on the impact of the chemical *milieu*, or changes thereof, on aquatic fauna and flora.

For the above and other reasons, a biomonitoring programme was developed for South Africa (Hohls, 1996) which uses riverine and riparian biota as well as riverine habitat status to assess the water quality and habitat integrity of rivers and streams. The biomonitoring programme is carried out under the umbrella of a national initiative known as the River Health Programme (www.csir.co.za/rhp). The programme makes use of a number of indices to describe the state of rivers within certain selected catchments around the country. The ultimate goal of the programme is to provide meaningful and accurate data, on both the water quality and overall condition of a water resource, which can then be used as the basis of sound management decisions regarding that particular resource. The previously used indices include aquatic invertebrate fauna, fish, riparian vegetation and river habitats. Up till now, this programme has included no aquatic autotrophic organisms in the monitoring regime, the lowest trophic level being aquatic invertebrate fauna.

Algae are widely used for river quality assessments (Prygiel et al., 1999; Whitton & Kelly 1995; Rott et al., 2003) and are regaining importance in Europe due to the reinforcement of the legislation with the Urban Wastewater Directives (EEC, 1991), more recently the Water Framework Directive (EC, 2000) indicates that the phytobenthos may be used as a relevant indicator of water quality. The diatoms form a large component of the attached flora found on various substrata in rivers and streams. The community composition of these attached or locally motile organisms is directly impacted by the chemical and physical characteristics of the surrounding water body. Undoubtedly diatoms are the most largely used phytobenthic algae (Stevenson & Pan, 2003). The advantages of using these organisms have been well-described (McCormick & Cairns, 1994; Reid et al., 1995). With the exception of Patrick et al. (1954) in the USA who developed a methodology based on structure of diatom assemblages, early methodology using diatoms as indicators of water quality largely originated from Europe in the framework of the saprobic system. At first, methods were devoted to monitoring organic pollution and afterwards for salinity, eutrophication, acidification, and general water quality (Ector & Rimet, 2005; Kelly, 1998; Prygiel et al., 1999; Rott et al., 2003). Numerous studies describing relationships between European diatoms indices and water chemistry have been carried out by specific programs (Lecointe et al., in Ector et al., 1999) and largely confirmed the validity of diatom indices for monitoring rivers in Europe (Dokulil et al., 1997; Eloranta & Soininen, 2002; Kwandrans et al., 1998; Montesanto et al., 1999) but also on other continents (Fawzi et al., 2002; Rott et al., 1998; Sgro & Johansen, 1998). It should be clear that if European indices can give a good indication of the river water quality, they have to be optimized. A preliminary examination of the regional situation is needed before applying diatom indication methods (Rott et al., 2003).

Recently the potential of diatom indices for monitoring water quality in rivers and streams has been explored by authors such as de la Rey et al. (2004) and Taylor et al. (2007) who found that index scores accurately reflected present conditions as well as being useful to back cast water quality (Taylor et al., 2005). Diatoms have also been used as indicators of water quality in the recent assessment of the state of the rivers in the Crocodile West and Marico water management area (Crocodile West and Marico WMA) as part of the national River Health Programme (River Health Programme, 2005). Diatom indices developed in France and other parts of Europe were used in the South African context to provide a numerical reflection of water quality as well as to classify the rivers and streams in a particular water quality class.

Concerns have been raised as to the transfer and comparison of biomonitoring data between the Northern and Southern Hemispheres. It is well known that some species have the same morphology, but questions still remain regarding the range of ecological tolerances of the various species. Concerns about ecological tolerances are valid when distance, climatic condition, and other environmental pressures are taken into account (Round, 1991). However, the present study has provided evidence for the concept discussed by Kelly et al. (1998), namely that diatoms are ''sub-cosmopolitan'' meaning that they may potentially occur anywhere in the world where a certain set of environmental conditions exist which favour the proliferation of a particular species (Padisák, 1998). The sub-cosmopolitan concept suggests that geographical location is not the determining factor in the distribution of diatom species and the composition of communities, but it is rather the specific environmental variables at a site that determine this distribution.

Up to the present only diatom indices developed elsewhere have been used and tested in South Africa. The application of the indices was possible because of the cosmopolitan distribution of many common diatoms as discussed above. Taylor et al. (2007) found that most species (98%) of benthic diatoms present in the heavily impacted Vaal River in central South Africa were cosmopolitan. However, even under these heavily polluted conditions (high nutrient load, high pH and high salinity), a few possibly endemic species may be found; for a discussion on this topic see Taylor & Lange-Bertalot (2006). The level of endemism may increase dramatically in smaller streams having a better water quality. For example, a distinctive species of *Achananthes* (*Achnanthidium*), *A. standeri* was described by Cholnoky, and is found in abundance in certain mountain streams (Cholnoky, 1957). The occurrence of these endemic species will necessitate the eventual development of unique diatom indices for accurate water quality assessment in South Africa.

This paper presents the relationship between measured water quality in the Crocodile West and Marico WMA and diatom index scores. This paper also shows that many widely distributed diatom taxa have similar environmental tolerances as compared to data recorded from Europe and elsewhere. Several problems encountered when using European diatom indices in South Africa are discussed.

Materials and methods

Study region

The Crocodile West and Marico water management area (Fig. 1) borders on Botswana to the north-west. The catchment is spread across three provinces (Gauteng, North West Province and Limpopo). Its main rivers, the Crocodile and Marico, give rise to the Limpopo River at their confluence. The climate is generally semi-arid. Extensive irrigation as well as grain, livestock and game farming occur in the catchment. Economic activity in the water management area is dominated by the urban and industrial complexes of northern Johannesburg and Pretoria together with platinum mining, north-east of Rustenburg. The Crocodile West and Marico water management area is the second most populous water management area in the country. Usage of surface water naturally occurring in the water management area has reached its potential and is being fully utilised. Large dolomitic groundwater aquifers occur along the southern part of the water management area. These are extensively utilised for urban and irrigation purposes. Some aquifers also underlie the border with Botswana and are shared with that country. A substantial portion of the water used in the water management area, is transferred into the area from the Vaal River and further afield. Transfers out of the water management area are to Gabarone in Botswana as well as to Nylstroom in the Limpopo water management area. Increasing quantities of effluent return flow from the urban/industrial areas are a major source of nutrients, salts and changes in pH in some rivers (DWAF, 2004).

Chemical and biological sample collection

Fifty diatom samples were collected during the period 29/06/2004 to 25/07/2004 in the Crocodile-Marico Catchment. Diatom samples were

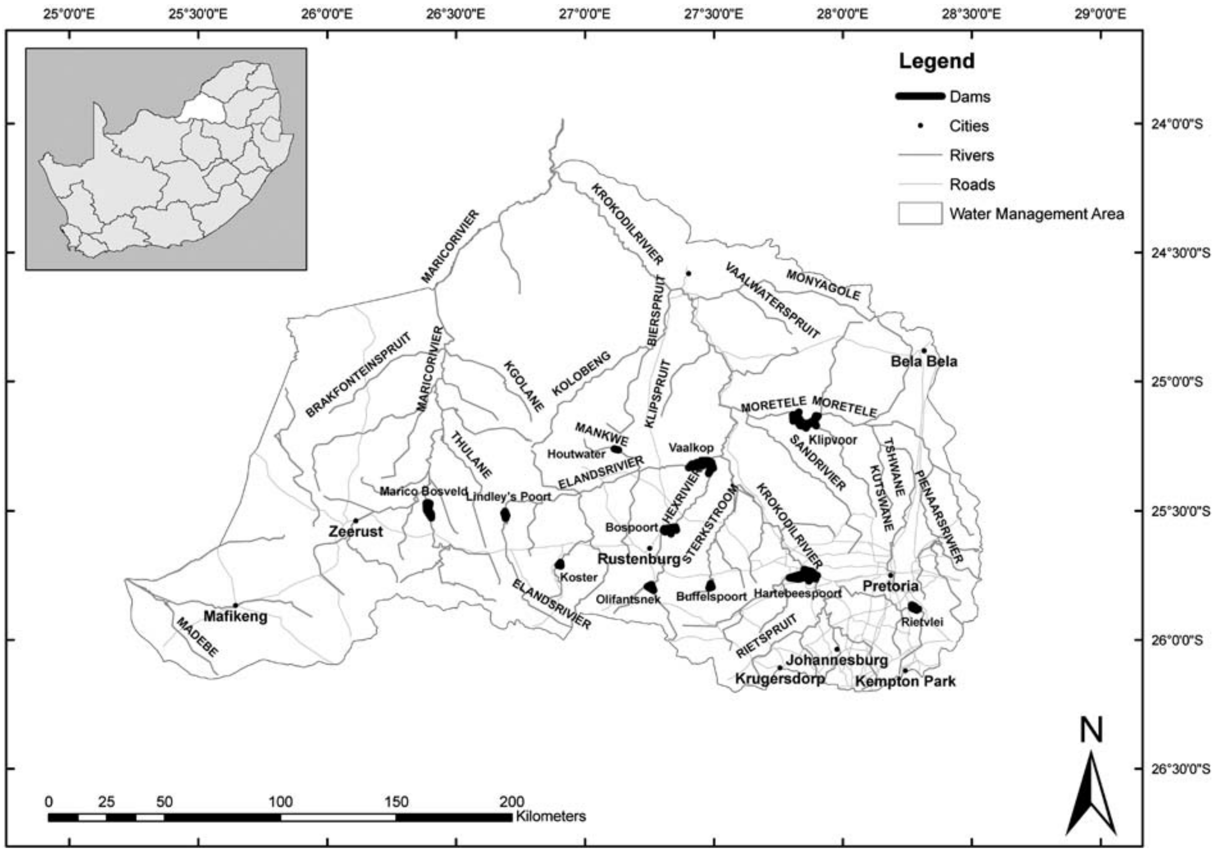

Fig. 1 Map showing location of some of the larger rivers in the Crocodile West and Marico water management area

collected and prepared using standard methods as summarised by Taylor et al. (2005). The diatom communities were then analysed by counting between 400 and 450 valves. The flora of Krammer & Lange-Bertalot (1986–1991) was used for identification. Other taxonomic guides consulted include Schoeman & Archibald (1976–1980), Round et al. (1990), Hartley (1996) and Prygiel & Coste (2000). For revised nomenclature the works of Lange-Bertalot (2001), Krammer (2002) and Kellogg & Kellogg (2002) were consulted. The community counts were entered into the diatom database and index calculation tool OMNIDIA version 3.1 (Lecointe et al., 1993) and several diatom indices were calculated.

The indices tested in the present study are known as the Generic Diatom Index or GDI (Coste & Ayphassorho, 1991), the Specific Pollution sensitivity Index or SPI (Coste in Cemagref, 1982), the Biological Diatom Index or BDI (Lenoir & Coste, 1996), the Artois-Picardie Diatom Index or APDI (Prygiel et al., 1996), Sládeček's index or SLA (Sládeček, 1986), the Eutrophication/Pollution Index or EPI (Dell'Uomo, 1996), Rott's Index or ROT (Rott, 1991), Leclercq and Maquet's Index or LMI (Leclercq & Maquet, 1987), the Commission of Economical Community Index or CEC (Descy & Coste, 1991) Schiefele and Schreiner's index or SHE (Schiefele & Schreiner, 1991), the Trophic Diatom Index or TDI (Kelly & Whitton, 1995), and the Watanabe index or WAT (Watanabe et al., 1986). In all cases except in the CEC, SHE, TDI and WAT index, the diatom indices were calculated using the formula of Zelinka & Marvan (1961). For all of the above indices, except TDI (maximum value of 100), the maximum value of 5 (converted to 20 by the software package OMNIDIA; Lecointe et al., 1993) indicates pristine water.

The Department of Water Affairs and Forestry (DWAF) collected the water quality data used in this study as part of their National Chemical

Monitoring Programme. The samples collected for this programme are analysed in the laboratories of Resource Quality Services (RQS), Pretoria, and the data is stored on DWAF's database and information management system, namely the Water Management System (WMS) from which the environmental data were drawn.

All chemical data was normalized using $\log_{10}$ transformation with the exception of the data recorded for pH. Pearson correlation was used to determine the relationship between the calculated index scores and the measured water quality variables and was carried out in STATISTICA version. 6.1.

Canonical Correspondence Analysis (CCA), using CANOCO version 4.5 (Ter Braak & Šmilauer, 1998), was used to determine the relationship between diatom assemblages and measured environmental variables. Abbreviations used in the CCA diagram may be found in Table 1.

Results

The results of the correlation analysis between measured environmental variables and diatom index scores generated for sites in the Crocodile West and Marico WMA are presented in Table 2.

The results of the Canonical Correspondence Analysis (CCA) are presented in Fig. 2. The first four axes of the species-environment plot accounted for 71% of the total variance in the community due to measured environmental variables (Table 3). Measured values (mean, median, minimum and maximum) for the physical and chemical variables ($n = 50$) in the Crocodile West and Marico WMA are presented in Table 4. These values include the calculated mean for the chemical variables; this value can be equated with the epicentre of the CCA plot. A summary of the acronyms used in Fig. 2 may be found in Table 1.

Discussion

In general, the diatom indices show significant correlations to water quality ($P < 0.05$). The correlations obtained in the present study are comparable to those demonstrated by Taylor et al. (2007) in South Africa and by Kwandrans

Table 1 Acronyms used in the CCA biplot (Fig. 2)

Taxon	Acronym
Achnanthidium minutissimum (Kützing) Czarnecki	ADMI
Achnanthidium affine (Grunow) Czarnecki	AMAF
Achnanthidium saprophila (Kobayasi & Mayama) Round & Bukhtiyarova	ADSA
Amphora pediculus (Kützing) Grunow	APED
Cocconeis placentula var. *euglypta* (Ehrenberg) Grunow	CPLE
Cymbella kappii (Cholnoky) Cholnoky	CKAP
Diatoma vulgaris Bory	DVUL
Encyonopsis microcephala (Grunow) Krammer	ENCM
Eolimna subminuscula (Manguin) Lange-Bertalot & Metzeltin	ESBM
Fragilaria capucina var. *rumpens* (Kützing) Lange-Bertalot	FCRU
Gomphonema minutum (Agardh) Agardh	GMIN
Gomphonema parvulum Kützing	GPAR
Gomphonema parvulum var. *lagenula* (Kützing) Frenguelli	GPLA
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot	GPUM
Navicula cryptocephala Kützing	NCRY
Navicula tripunctata (O.Müller) Bory	NTPT
Nitzschia archibaldii Lange-Bertalot	NIAR
Nitzschia dissipata (Kützing) Grunow	NDIS
Nitzschia frustulum (Kützing)Grunow	NIFR
Nitzschia paleacea (Grunow) Grunow *in* Van Heurk	NPAE
Navicula tenelloides Hustedt	NTEN
Total alkalinity	TAL
Electrical conductivity	Cond
Temperature	Temp

Table 2 Pearson correlation coefficients between measured environmental variables and diatom index scores generated for sites in the Crocodile West and Marico WMA

	SPI	SLA	LMI	SHE	WAT	TDI	EPI	ROT	GDI	CEC	BDI	APDI
Temperature	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·
EC mS/m	0.48	0.54	0.53	0.52	–0.40	0.66	0.56	0.55	0.55	0.52	0.60	–0.53
pH	–0.4	0.25	0.36	0.31	· · ·	0.31	0.30	0.29	0.55	0.42	0.49	–0.34
PO_4–P	0.44	0.41	0.48	0.45	–0.45	0.28	0.55	0.49	0.28	0.45	0.30	–0.49
NO_3 + NO_2–N	0.50	0.59	0.51	0.59	–0.49	0.55	0.55	0.63	0.23	0.45	0.40	–0.50
NH_4–N	0.51	0.39	0.40	0.39	· · ·	0.18	0.27	0.28	0.25	0.39	0.28	–0.29
Total alkalinity	0.34	0.42	0.37	0.40	–0.18	0.59	0.39	0.40	0.42	0.38	0.42	–0.33
Na^+	0.67	0.69	0.69	0.68	–0.52	0.75	0.76	0.66	0.60	0.70	0.71	–0.68
Mg^{2+}	0.50	0.57	0.52	0.57	–0.36	0.72	0.54	0.55	0.50	0.52	0.55	–0.50
SiO_2–S	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·
SO_4^{2-}	0.69	0.73	0.68	0.70	–0.49	0.83	0.75	0.66	0.64	0.71	0.74	–0.67
Cl^-	0.70	0.70	0.71	0.68	–0.54	0.77	0.79	0.67	0.64	0.73	0.73	–0.70
K^+	0.53	0.54	0.57	0.52	–0.46	0.59	0.60	0.55	0.49	0.57	0.60	–0.57
Ca^+	0.42	0.48	0.44	0.45	–0.29	0.59	0.48	0.45	0.42	0.45	0.45	–0.43
COD[a]	0.45	0.43	0.59	0.50	0.50	· · ·	0.45	0.61	· · ·	0.39	· · ·	0.57

Numerical values indicate significant correlations at $P < 0.05$, $n = 50$ (casewise deletion of missing data), while (· · ·) indicates no significant correlation. SPI: Specific Pollution Sensitivity Index, SLA: Sládeček's Index, LMI: Leclercq & Maquet's Index, SHE: Schiefele and Schreiner's Index, WAT: Watanabe's Index, TDI: Trophic Diatom Index, EPI: Eutrophication/Pollution Index, ROT: Rott's Index, GDI: Generic Diatom Index, CEC: Council for European Communities Index, BDI: Biological Diatom Index, APDI: Artois-Picardie Diatom Index

[a] $n = 40$

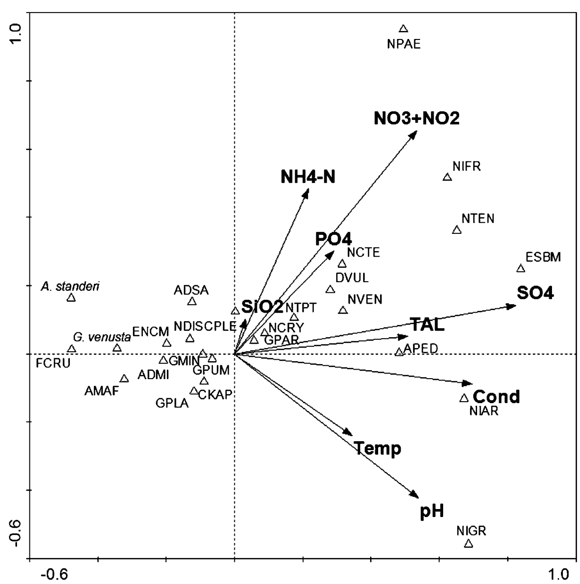

Fig. 2 CCA biplot showing the relationship between measured environmental variables and some diatom species in the Crocodile West and Marico water management area. Species with a weight range of 1–100% are shown. Acronyms are presented in Table 1

et al. (1998), Prygiel & Coste (1993) and Prygiel et al. (1999) in Europe. Significant correlations indicate the success with which diatom indices may be used to reflect changes in general water quality (Table 2) and organic pollution (as reflected by COD; Table 2). Temperature did not correlate significantly with any of the indices and this may be due to differing temperature regimes between Europe and South Africa, or due to different temperature tolerance of South African diatoms. Changes in temperature are more likely to be associated in South Africa with stream depth than with temperature, as even in winter, shallow streams and canals heat up very quickly (unpubl. data) while deeper streams and rivers tend to be more thermally stable e.g. the Vaal River (Taylor, 2004).

CCA (Fig. 2) was used to demonstrate that certain widely distributed taxa have similar ecological characteristics in widely separated geographic areas. It is clear from Fig. 2 that those species commonly associated with poor water quality in Europe e.g. *Eolimna subminuscula* Lange-Bertalot, *Nitzschia frustulum* (Kützing) Grunow ordinate on the right hand side of the diagram together with elevated levels of water quality variables. Another typical example is *Diatoma vulgaris* Bory, which commonly occurs worldwide in freshwaters with elevated levels of

Table 3 Summary of the canonical correspondence analysis (CCA) for the Crocodile West and Marico WMA

	Axis order			
	1	2	3	4
Eigenvalue	0.71	0.38	0.33	0.27
Species-environment correlation	0.95	0.84	0.86	0.75
Cumulative percentage variance of				
Species data	9.1	13.9	18.2	21.7
Species–environment relation	30.3	46.3	60.5	72

phosphate-phosphorus and is closely associated with the vector for this variable in Fig. 2. Taxa typical of cleaner, less impacted waters ordinate out on the left hand side of the diagram e.g. *Achananthidium minutissimum*, *Achnanthidium affine* (Grunow) Czarnecki, *Encyonopsis microcephala* (Grunow) Krammer and *Fragilaria capucina* var. *rumpens* (Kützing) Lange-Bertalot. This diagram helps to demonstrate that the widely distributed species encountered in the Crocodile West and Marico WMA are not simply just morphologically similar to those encountered in Europe, but have similar environmental tolerances.

Achnanthes standeri Cholnoky and *Gomphonema venusta* Passy, Kociolek & Lowe are shown in Fig. 2 on the far left hand of the ordination diagram. Thus far, these two species have only been recorded from South Africa; therefore, there is a strong likelihood that these two species are endemic. Both of these species were recorded as dominant (<5% of species relative abundance) in several samples, but did not dominate at all the sites. These two species are not included in any of the index calculations and their omission could result in an under or overestimation of the index scores.

The above evidence would suggest that although European diatom indices may be used in South Africa there are several problems to be considered:

(i) The list of taxa included in the indices needs to be adapted to the studied region. Most European diatom indices may be used in many regions and also in South Africa as they are based on the ecology of widely distributed or cosmopolitan taxa. This is particularly true for organic pollution as indicative taxa are ubiquitous and in addition, many European indices are based on Cholnoky's (1968) data for heterotrophy. Special attention should be paid to taxa occurring in pristine water (e.g. *Achnanthes standeri*) as well as endemic taxa which are absent in the indices reference lists (e.g. *Gomphonema venusta*). When these taxa are abundant, water quality may be misinterpreted.

(ii) Diatom taxonomy is undergoing rapid changes, especially at the genus level. Local floras, guides and methods to be used must be consistent. Some European indices have

Table 4 Summary table of measured chemical and physical environmental variables in the Crocodile West and Marico WMA during the study period ($n = 50$)

	Unit	Mean	SE	Median	SD	Range	Min.	Max.
Temperature	°C	13.49	0.63	12.54	4.42	21.10	5.90	27.00
Conductivity	mS/m	44.62	5.94	26.45	41.99	153.60	1.70	155.30
pH		7.56	0.10	7.52	0.74	3.43	5.87	9.30
$NO_3 + NO_2$–N	mg/ℓ	4.57	3.23	0.06	22.84	159.00	0.03	159.03
NH_4–N	mg/ℓ	0.06	0.04	0.02	0.28	2.00	0.02	2.01
TAL	mg/ℓ	124.33	11.59	136.29	81.97	300.00	4.00	304.00
Na^+	mg/ℓ	31.94	5.88	10.31	41.56	209.11	2.54	211.66
Mg^{2+}	mg/ℓ	20.46	2.48	17.40	17.54	72.30	1.37	73.67
SiO_2–S	mg/ℓ	6.21	0.43	5.86	3.06	17.07	0.01	17.08
PO_4–P	mg/ℓ	3.83	3.66	0.01	25.89	183.15	0.01	183.17
SO_4^{2-}	mg/ℓ	43.85	7.95	9.72	56.20	212.99	3.00	215.99
Cl^-	mg/ℓ	43.31	8.71	8.21	61.59	253.63	2.50	256.13
K^+	mg/ℓ	6.47	3.09	1.40	21.83	154.69	0.31	155.00
Ca^+	mg/ℓ	53.55	20.79	28.25	147.04	1051.77	2.05	1053.81

been proposed in the seventies or in the eighties and have never been revised. Thus, several common and abundant taxa, some of which being newly or recently described, may not be taken into account and lead to erroneous results. There are also several different approaches to taxonomy when calculating index scores. For example, *Achnanthidium pyrenaicum* (Hustedt) Kobayasi is part of the BDI taxa list, even if lumped with *Achnanthidium minutissimum* (Kützing) Czarnecki, but is not considered in other European indices such as TDI for example. Such an exclusion will possibly change index scores as these two taxa have a different ecology, *A. pyrenaicum* is characteristic of pristine calcareous rivers and *A. minutissimum* is considered as a cosmopolitan pioneer taxon. In the case of BDI, many taxa have been lumped because of the difficulty to separate them in routine surveillance, even if their ecology is different.

(iii) It has been highlighted in other studies that classification systems based on species tolerances should be carefully considered as built, to a greater or lesser extent, from local data. For example, Rott et al. (2003) noted that when using BDI, resulting index scores classified Austrian rivers as relatively good, even though large nutrient loads should have lead then to be classified as eutrophic, poor quality rivers. It should be noted that BDI was developed from data collected from the French national monitoring network which was aimed almost solely at monitoring impacts on water quality.

Conclusions

It is concluded that the index approach is deemed useful in South Africa to provide information on water quality impacts on rivers and streams. It has also been demonstrated that many widely distributed diatom species have similar environmental tolerances to those recorded for these species in Europe and elsewhere. However, the occurrence of possible endemic species will necessitate the eventual compilation of a diatom index unique to South Africa. In the mean time, diatom indices can be used in (a) gaining support and recognition for diatom-based approaches to water quality monitoring, (b) providing an indication of water quality for programmes such as the RHP and allowing for the dissemination of simplified useful information to resource managers, conservationists and the general public, and (c) allowing for sample and data collection which can then be used later in the formulation of a unique South African diatom index.

Acknowledgments The authors would like to thank the Department of Water Affairs and Forestry, Resource Quality Services for providing the chemical data used in this paper, Mrs. Shael Koekemoer who collected some of the diatom samples and Mr. G. P. Kriel for drawing the map.

References

Cemagref, 1982. Etude des methods biologiques d'appréciation quantitative de la qualité des eaux. Rapport Q. E. Lyon, Agence de l'eau Rhône-Méditerranée-Corse-Cemagref, Lyon, France.

Cholnoky, B. J., 1957. Über die diatomeen flora einiger gewaesser in den Magalies-Bergen nahe Rustenburg (Transvaal). Botanica Notiser 110: 332–362.

Cholnoky, B. J., 1968. Die Ökologie der Diatomeen in Binnengewässern. J Cramer, Lehre.

Coste, M. & H. Ayphassorho, 1991. Étude de la qualité des eaux du Bassin Artois-Picardie à l'aide des communautés de diatomées benthiques (application des indices diatomiques). Rapport Cemagref. Bordeaux - Agence de l'Eau Artois-Picardie, Douai.

De la Rey, P. A., J. C. Taylor, A. Laas, L. van Rensburg & A. Vosloo, 2004. Determining the possible application value of diatoms as indicators of general water quality: A comparison with SASS 5. Water SA 30: 325–332.

Dell'Uomo, A., 1996. Assessment of water quality of an Apennine river as a pilot study. In Whitton, B. A. & E. Rott (eds), Use of Algae for Monitoring Rivers II. Institut für Botanik, Universität Innsbruck, 65–73.

Descy, J.-P. & M. Coste, 1991. A test of methods for assessing water quality based on diatoms. Verhandlungen der Internationalen Vereinigung für theoretische und angewandte Limnologie 24: 2112–2116.

Dokulil, M. T., R. Schmidt & S. Kofler, 1997. Benthic diatom assemblages as indicators of water quality in an urban flood-water inpoundment, Neue Donau, Vienna, Austria. Nova Hedwigia 65: 273–283.

DWAF, 2004. National Water Resources Strategy, 1st edn. Department: Water Affairs and Forestry, Pretoria.

Ector, L. & F. Rimet, 2005. Using bioindicators to assess rivers in Europe: An overview. In Lek, S., M. Scardi, P. F. M. Verdonschot & Y. S. Park (eds), Modelling Community Structure in Freshwater Ecosystems. Springer Verlag, Berlin, 1–19.

Ector, L., A. Loncin & L. Hoffmann, 1999. Compte rendu du 17e colloque de l'Association des diatomistes de langue française. Cryptogamie - Algologie 20: 105–148.

Eloranta, P. & J. Soininen, 2002. Ecological status of some Finnish rivers evaluated using benthic diatom communities. Journal of Applied Phycology 14: 1–7.

EC, 2000. Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities, L 327/1.

EEC, 1991. Council directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC), Official Journal of the European Communities, L 135/40, 1991: 40–52.

Fawzi, B., M. Loudiki, S. Oubraim, B. Sabour & M. Chlaida, 2002. Impact of wastewater effluent on the diatom assemblages structure of a brackish small stream: Oued Hassar (Morocco). Limnologica 32: 54–65.

Hartley, R., 1996. An atlas of British diatoms. Biopress Ltd., Bristol.

Hohls, B. R., 1996. National biomonitoring programme for riverine ecosystems: Framework document for the programme. NBP report series No. 1. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria.

Kellogg, B. & D. E. Kellogg, 2002. Diatom Monographs. Vol. 1. Non-Marine and Littoral Diatoms from Antarctic and Subantarctic regions: Distribution and Updated Taxonomy. ARG Gantner Varlag Kommanditgesellschaft, Ruggell.

Kelly, M. G., 1998. Use of community-based indices to monitor eutrophication in European rivers. Environmental Conservation 25: 22–29.

Kelly, M. G. & B. A. Whitton, 1995. The trophic diatom index: a new index for monitoring eutrophication in rivers. Journal of Applied Phycology 7: 433–444.

Kelly, M. G., A. Cazaubon, E. Coring, A. Dell'Uomo, L. Ector, B. Goldsmith, H. Guasch, J. Hürlimann, A. Jarlman, B. Kawecka, J. Kwandrans, R. Laugaste, E. A. Lindstrøm, M. Leitao, P. Marvan, J. Padisák, E. Pipp, J. Prygiel, E. Rott, S. Sabater, H. Van Dam & J. Vizinet, 1998. Recommendations for the routine sampling of diatoms for water quality assessments in Europe. Journal of Applied Phycology 10: 215–224.

Krammer, K., 2002. Diatoms of Europe. Diatoms of European Waters and Comparable Habitats, Vol. 3. ARG Gantner Varlag Kommanditgesellschaft, Ruggell.

Krammer, K. & H. Lange-Bertalot, 1986–1991. Süßwasserflora von Mitteleuropa. Band 2. Bacillariophyceae. Teil 1–4. Gustav Fischer Verlag, Stuttgart. Germany.

Kwandrans, J., P. Eloranta, B. Kawecka & K. Wojtan, 1998. Use of benthic diatom communities to evaluate water quality in rivers of southern Poland. Journal of Applied Phycology 10: 193–201.

Lange-Bertalot, H., 2001. Diatoms of Europe. Diatoms of European Waters and Comparable Habitats, Vol. 2. ARG Gantner Varlag Kommanditgesellschaft, Ruggell.

Leclerq, L. & B. Maquet, 1987. Deux nouveaux indices chimique et diatomique de qualité d'eau courante. Application au Samson et à ses affluents (bassin de la Meuse belge). Comparaison avec d'autres indices chimiques, biocénotiques et diatomiques. Institut Royal des Sciences Naturelles de Belgique, document de travail 28.

Lecointe, C., M. Coste & J. Prygiel, 1993. ''Omnidia'': Software for taxonomy, calculation of diatom indices and inventories management. Hydrobiology 269/270: 509–513.

Lenoir, A. & M. Coste, 1996. Development of a practical diatom index of overall water quality applicable to the French National Water Board network. In Whitton, B. A. & E. Rott (eds), Use of Algae for Monitoring Rivers II. Institut für Botanik. Universität Innsbruck, 29–43.

McCormick, P. V. & J. J. Cairns, 1994. Algae as indicators of environmental change. Journal of Applied Phycology 6: 509–526.

Montesanto, B., S. Ziller & M. Coste, 1999. Diatomées épilithiques et qualité biologique des ruisseaux de mont Stratonikon, Chalkidiki (Grèce). Cryptogamie - Algologie 20: 235–251.

Padisák, J., 1998, The Phytoplankton. In O'Sullivan, P. & C. S. Reynolds (eds), The Lakes Handbook. Blackwell Science Ltd, Oxford.

Patrick, R., M. H. Hohn & J. H. Wallace, 1954. A new method for determining the pattern of the diatom flora. Notulae Naturae 259: 2–12.

Prygiel, J. & M. Coste, 1993. Utilisation des indices diatomiques pour la mesure de la qualité des eaux du bassin Artois-Picardie: bilan et perspectives. Annales of Limnology 29: 225–267.

Prygiel, J. & M. Coste, 2000. Guide méthodologique pour la mise en œuvre de l'indice Biologique Diatomées NF T 90-354. Agences de l'Eau-Cemagref de Bordeaux, mai 2000, 134 pages + Clés de déetrmination (89 planches) + cédérom français-anglais (tax'IBD).

Prygiel, J., M. Coste & J. Bukowska, 1999. Review of the major diatom-based techniques for the quality assessment of rivers - State of the art in Europe. In Prygiel, J., B. A. Whitton & J. Bukowska (eds), Use Of Algae for Monitoring Rivers III. Agence de l'Eau Artois- Picardie, France.

Prygiel, J., L. Lévêque & R. Iserentant, 1996. Un nouvel indice diatomique pratique pour l'évaluation de la qualité des eaux en réseau de surveillance. Revue des Sciences de l'Eau 1: 97–113.

Reid, M. A., J. C. Tibby D. Penny & P. A. Gell, 1995. The use of diatoms to assess past and present water quality. Australian Journal of Ecology 20: 57–64.

River Health Programme, 2005. State-of-Rivers Report: Monitoring and Managing the ecological State of Rivers in the Crocodile (West) Marico Water Management Area. Department of Environmental Affairs and Tourism. Pretoria.

Rott, E., 1991. Methodological aspects and perspectives in the use of periphyton for monitoring and protecting rivers. In Whitton, B. A., E. Rott & G. Friedrich (eds), Use of Algae for Monitoring Rivers. Institut fur Botanik, Univ. Innsbruck, 9–16.

Rott, E., H. C. Duthie & E. Pipp, 1998. Monitoring organic pollution and eutrophication in the Grand River, Ontario, by means of diatoms. Canadian Journal of Fisheries and Aquatic Sciences 55: 1443–1453.

Rott, E., E. Pipp & P. Pfister, 2003. Diatom methods developed for river quality assessment in Austria and a cross-check against numerical trophic indication methods used in Europe. Algological Studies 110: 91–115.

Round, F. E., 1991. Diatoms in river water-monitoring studies. Journal of Applied Phycology 3: 129–145.

Round, F. E., R. M. Crawford & D. G. Mann, 1990. The Diatoms: Biology and Morphology of the Genera. Cambridge University Press, Cambridge.

Schoeman, F. R. & R. E. M. Archibald, 1976–1980. The Diatom Flora of Southern Africa. National Institute for Water Research, Pretoria.

Schiefele, S. & C. Schreiner, 1991. Use of diatoms for monitoring nutrient enrichment acidification and impact salts in Germany and Austria. In Whitton, B. A., E. Rott & G. Friedrich (eds), Use of Algae for Monitoring Rivers. Institüt für Botanik, Univ. Innsbruk.

Sgro, G. V. & J. R. Johansen, 1998. Algal Periphyton Bioassessment Methods For Lake Erie Estuaries, Vol. 1, Metric Development. Lake Erie Office, Toledo, Ohio.

Slàdeček, V., 1986. Diatoms as indicators of organic pollution. Acta Hydrochimica et Hydrobiologica 14: 555–566.

Stevenson, R. J. & Y. Pan, 2003. Assessing environmental conditions in rivers and streams with diatoms. In Stoermer, E. F. & J. P. Smol (eds), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, 11–40.

Taylor, J. C., 2004. The application of diatom-based pollution indices in the Vaal catchment. Unpublished M.Sc. thesis, North-West University, Potchefstroom Campus, Potchefstroom.

Taylor, J. C. & H. Lange-Bertalot, 2006. *Eolimna archibaldii* spec. nov. and *Navigiolum adamantiforme* comb. nov. (Bacillariophyceae): Two possibly endemic elements of the South African diatom flora tolerant to surface water pollution. African Journal of Aquatic Sciences 31: 175–183.

Taylor, J. C., P. A. de la Rey & L. van Rensburg, 2005. Recommendations for the collection, preparation and enumeration of diatoms from riverine habitats for water quality monitoring in South Africa. African Journal of Aquatic Sciences 30: 65–75.

Taylor, J. C., M. S. Janse van Vuuren & A. J. H. Pieterse, 2007. The application and testing of diatom-based indices in the Vaal and Wilge rivers, South Africa. Water SA 33: 51–60.

Ter Braak, C. J. F. & P. Šmilauer, 1998. CANOCO Reference Manual and User's Guide to Canoco for Windows: Software for Cannonical Community Ordination (version 4). Microcomputer Power, New York.

Watanabe, T., K. Asai & A. Houki, 1986. Numerical estimation of organic pollution of flowing waters by using the epilithic diatom assemblage - Diatom Assemblage Index (DIApo). Science of the Total Environment 55: 209–218.

Whitton, B. A. & M. G. Kelly, 1995. Use of algae and other plants for monitoring rivers. Australian Journal of Ecology 20: 45–56.

Zelinka, M. & P. Marvan, 1961. Zur Präzisierung der biologischen Klassifikation der Reinheit fliessender Gewässer. Archiv für Hydrobiologie 57: 389–407.