Review

Diatom-based water quality monitoring in southern Africa: challenges and future prospects

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ABSTRACT

Diatoms are of significant ecological importance in aquatic ecosystems, which stems from their dynamic position at the base of the trophic web as primary producers. Because diatom communities have specific environmental requirements and respond rapidly to changes in environmental conditions they are often employed as a cost-effective method to assess anthropogenic impacts and health statuses of aquatic ecosystems, particularly in Europe and North America. The purpose of this review is to summarise the challenges and future prospects associated with biological water quality monitoring using diatoms with special focus on southern Africa. Much work still needs to be carried out on diatom tolerances, ecological preferences and ecophysiology. It is recommended that past research pertaining to African diatom taxonomy should be made readily accessible to all through electronic media for use as a reference point. Moreover, following the same approach as for macroinvertebrate biomonitoring, African and other developing countries can resort to intermediate diatom taxonomy (i.e. genus), which is easier, less time-consuming and requires less-skilled personnel. While the lack of capacity and baseline information on diatom community composition and ecological requirements represent significant hurdles, diatom biomonitoring potentially holds much promise for understanding the ecological functioning and management of aquatic ecosystems in southern Africa. The application of diatom-based water quality assessment protocols has direct and immediate value for use as an 'added-value' assessment tool in addition to the use of macroinvertebrates and fish indices as these can indicate anthropogenically impacted and pristine sites.

Keywords: application, biomonitoring, ecology, taxonomy, rivers, water quality

INTRODUCTION

Aquatic ecosystems form a fundamental component of global biogeochemical cycles, acting as transport pathways, elemental transformations and storage sites (Wehr and Descy, 1998; Bere and Tundisi, 2010). These systems are characterised by a high degree of interaction and complexity among physical, chemical and biological processes. Aquatic ecosystems, e.g., rivers, often present a continuous gradient of physical, chemical and biological conditions that are frequently predictable (Vannote et al., 1980). An important feature of aquatic ecosystems is that a disturbance at one location, through conversion of landscapes into other uses such as agriculture, urban and industrial developments, often affects the functioning, processes and organisms downstream. This has serious implications for ecosystem functioning and for management of these systems (Ndaragu et al., 2004; Ndiritu et al., 2006).

Agricultural activities, e.g., irrigation and livestock, increase inputs of nutrients and sediments (Leland and Porter, 2000; Bere 2007), and urbanization contributes large quantities of organic wastewater and solids (Lobo et al., 1995; Beyene et al., 2009; Bere and Mangadze, 2014, Dalu et al., 2015), while industries are major sources of inorganic pollution (Beyene et al. 2009). Although information on the impacts of anthropogenic activities in river systems is well documented in developed countries (e.g. Dixit and Smol, 1994; Kelly et al., 2008, 2012; Stevenson, 2014), very little is known from most developing countries, yet such data are important for developing appropriate management practices (Fabricius et al., 2003; De la Rey et al., 2004, 2008; Taylor et al., 2007a; Bere and Tundisi, 2010) necessary to meet Millennium Development Goal 7, on ensuring environmental sustainability.

River systems are characterised by longitudinal differences in the physico-chemical and biotic fauna and flora making it difficult to design and implement management strategies due to their heterogeneous state (Bere and Tundisi, 2010). Ecological principles such as networks, flows and nested systems thus play an important role in determining the best management and policy options for these aquatic ecosystems (De la Rey et al., 2004). The characterisation and management of these dynamic physico-chemical and biological conditions in these heterogeneous systems requires innovative approaches, with many management processes attempting to strike a balance between ecological integrity and human needs (Fig. 1) (De la Rey et al., 2004; Stevenson, 2014).

Currently, two basic approaches to water quality assessment within river ecosystem health assessments are the assessment of physico-chemical variables, and biomonitoring (De la Rey et al., 2004; Bere and Tundisi, 2010). The assessment of physico-chemical variables in river systems to assess water quality allows only for instantaneous measurements, thereby restricting the knowledge of water conditions to the period when the measurements were taken (De la Rey et al., 2004), giving a 'snapshot' result that ignores temporal variation of physico-chemical variables. The monitoring of water chemistry typically also only involves the determination of macronutrient concentrations and measurement of selected physico-chemical variables including pH (De la Rey et al., 2004; Bere et al., 2013).

The second approach, biomonitoring, involves the use of aquatic organisms to assess their response to environmental change. Biomonitoring aims to provide a direct measure of ecological integrity through integration of various stressors. It allows

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long-term environmental effects to be detected, providing a broad measure of their synergistic impacts (Harding et al., 2004; Stevenson, 2014). Aquatic communities integrate and reflect the effects of environmental disturbances that occur over extended periods of time, thereby providing a holistic and an integrated measure of health (Chutter, 1998; Ndiritu et al., 2006). The main advantage of using a biological approach is that it examines organisms whose exposure to pollutants is continuous and the organisms present in aquatic ecosystems reflect both the past and present water quality history, allowing detection of environmental changes that might otherwise be overlooked using physico-chemical assessments (Pan et al., 1996; De la Rey et al., 2004).

The key to the use of aquatic organisms as reliable indicators of the environmental changes in aquatic ecosystems is untangling the integrated information in species assemblages and the environment (Pan et al., 1996). The use of biomonitoring has, therefore, gained momentum in aquatic ecosystem health management programmes due to the shortcomings in the physico-chemical variables based assessments (De la Rey et al., 2004). Biomonitoring is now viewed as an ideal means by which progress towards integrated water resource management can be monitored in that it provides an overview of environmental conditions (Passy, 2007; Stevenson, 2014; Bere, 2016a). As a consequence, biomonitoring is now viewed as an important branch of applied ecology where the ecological, scientific and economic interests of our society meet in the management of river systems (De la Rey et al., 2004; Passy, 2007; Stevenson, 2014).

The purpose of this review is to summarise the challenges and prospects for employing diatoms as a biomonitoring tool in water quality monitoring, with specific focus on the sub-Saharan African region.

Diatom use in biomonitoring

Diatoms comprise the major component of the microphytobenthos and form an integral part of primary producers in aquatic ecosystem food webs (Dalu et al., 2014a). Diatoms belong to the class Bacillariophyceae and comprise of a ubiquitous, highly successful and distinctive group of mostly unicellular algae, with the most obvious distinguishing characteristic being the presence of siliceous cell walls (frustules; Round et al., 1990). Because diatoms respond directly to growth stimulants such as nutrients (e.g. Lobo et al., 1995; Bere and Mangadze, 2014; Dalu et al., 2014a; Dalu and Froneman, 2014), physical factors such as habitat and elevation (e.g. Ndiritu et al., 2003, 2006; Passy et al., 2006; Dalu et al., 2014b) and/or stressors such as contaminants and habitat alterations (e.g. Lobo et al., 1995; Passy et al., 2006; Stevenson, 2014), they can be employed to monitor changes (natural and anthropogenic) within aquatic systems.

Diatoms have long been employed in ecological assessments for environmental change and pollution around the world (Bere and Tundisi, 2010; Stevenson et al., 2014). Studies by Bate et al. (2002), Bere and Tundisi (2010), Harding et al. (2014) and Stevenson (2014) present a global historical overview of diatom-based monitoring from the time Kolkwitz and Marsson (1908) first used diatoms in water monitoring to the present. Importantly, the global ability to use diatoms to evaluate present (e.g. Ndiritu et al., 2003, 2006; Ndaragu et al., 2004; Bere and Mangadze, 2014; Dalu et al., 2014c) and past conditions (e.g. Haberyn and Hecky, 1987; Stager and Johnson, 2000; Talbot and Lærdal, 2000; Taylor et al., 2005b; Harding and Taylor, 2014) had increased by the turn of the 21st century.

Biomonitoring programmes across sub-Saharan Africa commonly make use of several aquatic biological indicator organisms including fish (Fish Assemblage Integrity Index, e.g., Kleynhans, 1999; Kadye, 2008), macroinvertebrates (e.g. South African Scoring System (SASS); Chutter, 1998; Gratwicke, 1998; Mbaka et al., 2014; M'Erimba et al., 2014; Bere et al., 2016b) and macrophytes (e.g. Riparian Vegetation Index; Kemper, 2001). Until the turn of the century no biomonitoring method based on autotrophic organisms (diatoms) was routinely being used in African waters (De la Rey et al., 2004; Ndiritu et al., 2004, 2006), despite the fact that earlier African scholars had used diatoms as indicators of water quality (Table 1; e.g. Schoeman et al., 1979; Schoeman and Haworth, 1986; Pieterse and Van Zyl, 1988). Béla Jenö Cholnoky (1899–1972) known as 'the father of South African diatomology', placed little faith in performing only physico-chemical analyses for aquatic ecosystem water quality analysis, arguing that the physico-chemical characteristics of a water body could be determined more reliably and cost effectively through the study of associated diatom communities (Harding et al., 2005). The use of diatom biomonitoring, therefore, formed part of the Department of Water Affairs and Forestry (DWAF) of South Africa's National Aquatic Ecosystem

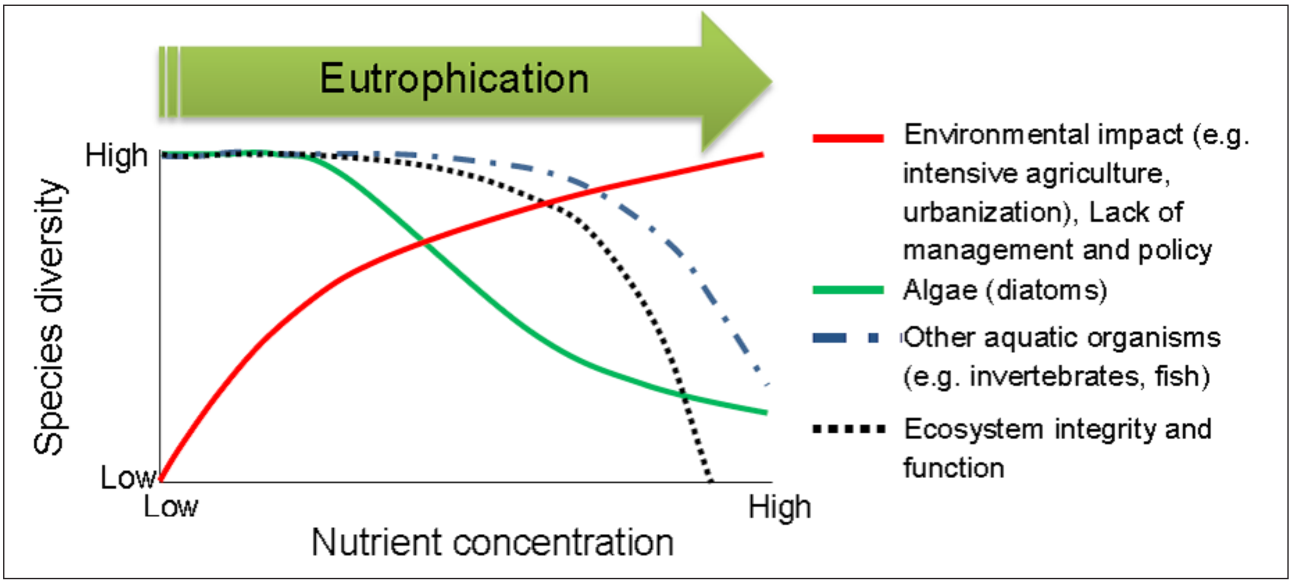

Figure 1
Environmental impact on aquatic biodiversity, ecological integrity and functioning of aquatic ecosystems. Modified from Stevenson (2014).

Biomonitoring Programme or River Health Programme (RHP) as it was considered cost effective and accurate, giving comparable data (De la Rey et al., 2004; Harding et al., 2004).

More recently, diatoms have increasingly been used for the assessment of short- and long-term water quality and environmental change (Fabricius et al., 2003; De la Rey et al., 2004; Taylor et al., 2007b; De la Rey et al., 2008; Bere and Tundisi, 2010; Bere et al., 2014) across the African continent. Diatom-based information can be gleaned not only from natural surfaces such as sediments, stones-in-current and marginal vegetation (macrophytes), but also from artificial substrates in aquatic ecosystems (De la Rey et al., 2004; Taylor et al., 2007; Bere and Tundisi, 2011; Dalu et al., 2014a, c; Dalu and Froneman, 2014). The use of artificial substrates has been key in the formulation of stressor-response models (Hirst et al., 2004; Lacoursière et al., 2011).

Diatom-based monitoring in southern Africa

Benthic diatom communities are sensitive indicators of environmental pollution, e.g., nutrient status, in aquatic ecosystems, which explains their widespread utilization across North America and Europe for routine determinations of river bio-integrity (Dixit and Smol, 1994; Lang et al., 2012; Stevenson, 2014). In developed countries, various environmental legislation statutory requirements, such as the Water Framework Directive 2000/60/EC in Europe (Kelly et al., 2008, 2012) and Environmental Monitoring and Assessment Program Surface Waters EPA/620/R-94/004F (EMAP-SW) in the United States of America (Dixit and Smol, 1994), have been developed to safeguard these aquatic ecosystems as they seek to evaluate the biotic integrity and trophic conditions.

In sub-Saharan Africa, South Africa (e.g. Schoeman et al., 1979; Schoeman and Haworth, 1986; Pieterse and Van Zyl, 1988; De la Rey et al., 2004, 2006; Harding et al., 2004; Taylor et al., 2007a, b; Taylor and Harding, 2014) has been the leader in environmental protection and the use of benthic diatoms in aquatic ecosystems to monitor biotic integrity, and trophic condition assessments are routinely used in both freshwater and estuarine systems (Taylor et al., 2007). In addition, Kenya has also implemented diatom biomonitoring programmes (e.g. Ndiritu et al., 2003; Ndaragu et al., 2004; Ndiritu et al., 2006; Triest et al., 2012), with other countries such as Zambia (Lang et al., 2012) and Zimbabwe (Bere et al., 2014; Bere and Mangadze, 2014) beginning to embrace the benefits of implementing diatom-based water quality assessments of their aquatic ecosystems. Despite the relative cost effectiveness of this approach, however, the practice of using diatoms to monitor anthropogenic impacts on river health in Africa has largely been ignored (Cocquyt et al., 2013).

In South Africa, Water Research Commission (WRC) funded projects have laid the foundation for the implementation and successful use of diatom-based monitoring programmes in both freshwater and estuarine ecosystems (Bate et al., 2002; Harding, 2004; Taylor et al., 2005a, 2007c, d; DH Environmental Consulting, 2015). In Zambia, the Southern African River Assessment Scheme (SAFRASS) study, funded by African, Caribbean and Pacific countries (ACP) Science and Technology Programme, spearheaded the development of a national diatom biomonitoring protocol, guides and procedures (Dallas et al., 2010; Lang et al., 2012). The importance of the provision of standardized methods has been recognised in Europe and America and has taken the form of recommended standard protocols (CEN, 2003; 2004; Kelly et al., 2012). Although the methods and techniques for diatom preparation for viewing under the microscope existed in Africa before the turn of the century (e.g. Schoeman and Archibald, 1977; Schoeman, 1982; Pieterse and Van Zyl, 1988), these methods often made use of harmful chemicals such as nitric and sulphuric acids (Harding et al., 2004; Taylor et al., 2007c). Consequently, techniques and methods for diatom collection, preparation and enumeration were tested and applied based on methods developed in Europe, for the recommendation of a standard set of procedures in South Africa (Harding et al., 2004; Taylor et al., 2005a; Taylor et al., 2007c, d).

Present legislation, e.g., the water and environmental acts, governing water resource management in many African countries (e.g. Botswana, Kenya, South Africa, Zambia, Zimbabwe) requires that river health, and aquatic ecosystem health, be assessed in order to determine user strategies and impacts of new developments on the environment (Harding et al., 2004). In support of these requirements, river health assessment protocols have been developed in South Africa (Harding et al., 2004; Taylor et al., 2007c, d; DH Environmental Consulting, 2015) and, more recently, in Zambia methodological recommendations have been developed (Dallas et al., 2010; Lang et al., 2012). The protocols need to be constantly refined as part of the river health policy implementation based on diatom monitoring as new diatoms are identified and ecological tolerances/preferences determined. Other African countries, e.g.,

TABLE 1
Published records of use of diatoms in water quality assessments (pre- and post-2000) from different countries of southern Africa

		YEAR	LOCALITY	SOURCE
PRE-2000	SOUTH AFRICA	1956-1957	Jukskei-Crocodile River	Cholnoky (1958)
		1968	South African rivers	Cholnoky (1968)
		1972	South African rivers	Archibald (1972)
		1976	Jukskei-Crocodile River	Schoeman (1976)
		1979	Hennops River	Schoeman (1979)
		1982	Jukskei-Crocodile River	Schoeman (1982)
		1986	Unknown location	Schoeman and Haworth (1986)
	MALAWI	1999	Lake Malawi	Hecky et al. (1999)

Table continues...

TABLE 1 (CONTINUED) Published records of use of diatoms in water quality assessments (pre- and post-2000) from different countries of southern Africa				
		YEAR	**LOCALITY**	**SOURCE**
POST-2000	KENYA	2003	Nairobi River	Ndiritu et al. (2003)
		2006	Gombe and Lake Tanganyika Rivers	Bellinger et al. (2006)
		2006	Central Kenya	Ndiritu et al. (2006)
	MALAWI	2003	Lake Malawi	Higgins et al. (2003)
		2012	Blantyre	Kaonga and Monjerezi (2012)
	SOUTH AFRICA	1956, 1957	Jukskei-Crocodile River	Taylor et al. (2005b)
		1960, 2008	Wemmershoek Catchment	Harding and Taylor (2014)
		2002	South African River systems	Bate et al. (2002)
		2002-2003	Vaal and Wilge Rivers	Taylor et al (2007e)
		2004	Swartkops River	Bate et al. (2004)
		2008	Mooi River	De La Rey et al. (2004)
		2005	South Africa	River Health Programme (2005)
		2005	South Africa	Taylor et al. (2005a)
		2007	South African River systems	García-Rodríguez et al. 2007
		2007	Berg, Kromme and Mngazi Estuaries	Snow (2007)
		2007	Vaal and Wilge Rivers	Taylor et al. (2007a)
		2007	Crocodile West and Marico Water Management Area	Taylor et al. (2007b)
		2008	St Lucia Estuary	Bate and Smailes (2008)
		2008	Marico-Molopo River catchment	De la Rey et al. (2008)
		2009	Buffelspoort Valley	Taylor et al. (2009)
		2009	Crocodile and Magalies Rivers	Walsh and Wepener (2009)
		2010	Skidaway River Estuary	Verity and Borkman (2010)
		2010-2012	Great Fish River	Holmes and Taylor (2015)
		2012-2013	Kowie River	Dalu et al. (2014d)
		2012-2013	Kowie River	Dalu et al. (2016)
		2013	Sundays River	Janse Van Vuuren and Taylor (2015)
	ZIMBABWE	2007	Sanyati Basin, Lake Kariba	Phiri et al. (2007)
		2007	Nyanga	Bere et al. (2013)
		2012	Chinhoyi	Bere and Mangadze (2014)
		2012	Chinhoyi	Bere et al. (2014)
		2013	Manyame Catchment	Mangadze et al. (2015)
		2007, 2012	Nyanga, Chinhoyi	Bere (2016a)
		2007	Eastern Highlands	Bere (2016b)
		2013	Manyame Catchment	Mangadze et al. (2016)

Zimbabwe, have adapted diatom protocols and methods and procedures developed in South Africa for use in river health monitoring (Bere and Mangadze, 2014; Bere et al., 2014).

Recently, diatom-based indices such as the Specific Pollution Index (SPI) and Biological Diatom Index (BDI) have come into the spotlight as potential additions to more established biological indicators such as SASS (De la Rey et al., 2008), with several studies being carried out over the past few years exploring the potential use of diatoms as biological indicators (De la Rey et al., 2004; Harding et al., 2005; Taylor et al., 2007a, b). A standard protocol for assessment using diatoms has also been published (Taylor et al., 2005a) to facilitate comparability of diatom index results. The value of diatoms as biological indicators has been recognized and formed part of the state of the rivers report for the Crocodile West–Marico Water Management Area in South Africa (River Health Programme, 2005; Taylor et al., 2007b; De la Rey et al., 2008).

Challenges and prospects in diatom-based monitoring in Africa

Round (1993) and De la Rey et al. (2004) have highlighted the benefits of using diatom-based biomonitoring programmes which bear special relevance to South Africa, Kenya and Zimbabwe. These include cost effectiveness, rapidity and accuracy of data collection, and that non-specialists with a biological background can do identifications and counts if they are provided with illustrated guides.

Concerns have, however, been raised by scholars on the confidence in results produced by non-specialists in diatom identification (Kociolek and Stoermer, 2001). The difficulties with diatom taxonomy and nomenclature can now, however, be addressed through recent technology advances enabling comparison of images with electronic keys and rapid e-mail communication with experts (De la Rey et al., 2004; Kociolek and Stoermer, 2001). Indeed, Kociolek and Stoermer (2001) propose that studies on the taxonomy and ecology of diatoms in the 21st Century must be linked through integrated research programmes, facilitated by technological advances that support both accurate taxonomy and improved ecological interpretation, such as through the use of powerful microscopes (i.e. electron microscopes). The authors' personal experience from using the most recent and powerful electron microscopes, supported by good identification guides, along with recently published literature, confirms in the possibility of a marked reduction in the time required for identification (taxonomy) and high confidence in the results obtained.

One major problem that has led to diatom-based biological monitoring not being widely employed is the lack of capacity and the training of diatom taxonomists due to limiting funding and job opportunities. Taxonomists tend to restrict themselves to identifying and naming species and often fail to consider the ecological context (i.e. species tolerances) of the different species. Such an approach limits funding and employment opportunities. The study of diatoms in southern Africa initially attracted a number of investigators who produced large volumes of published research (Harding et al., 2004). However, relatively few students were trained to extend their work. Moreover, the decision to focus on biomonitoring using macroinvertebrates in the 1980s further contributed to limited job opportunities for diatom specialists. As a consequence, South Africa now only has a handful of diatom experts (< 10). A select group of individuals with limited skills and training are attempting to continue diatom biomonitoring and ecology studies within the region. In South Africa, for example, the bulk of the diatom taxonomic work appears in the grey literature (formerly housed at the Council for Scientific and Industrial Research (CSIR) but now housed at the South African Institute for Aquatic Biodiversity (SAIAB) National Diatom Collection at North-West University, South Africa) and is not readily available to researchers using internet search engines. These data can, however, be accessed on request, but this can often be time consuming (Fig. 2, Table 2; see Harding et al. (2004) for further details). Furthermore, only a handful of papers and books relate to water quality assessment using diatoms. Moreover, most African research institutions and universities do not have the necessary facilities (such as powerful electron microscopes) and expertise to conduct routine diatom analyses. All these challenges have contributed to the difficulty of implementing diatom-based biological monitoring programmes in most sub-Saharan countries. Hence the field of diatoms has gained the reputation of being one of the most technically

TABLE 2
A breakdown of the total number of reprints and papers on diatom ecology and taxonomy that are estimated to be housed at the CSIR diatom collection. Bold text indicates data that has been electronically captured (Source: Harding et al., 2004)

Category	No. of papers	No. of boxes
Literature papers by box numbers	**5 453**	**196**
Papers by general author names	360	12
Papers on chemistry	200	8
Papers on ecological information	300	10
Papers on Africa	**1 365**	**39**
Papers by specific authors	**2 000**	**100**
Reprints and general papers	720	36

Figure 2
Selected diatom ecology and taxonomy reprints and publications at the South African Diatom Collection housed at the Council for Scientific and Industrial Research and since moved to South African Institute for Aquatic Biodiversity National Diatom Collection at North-West University, South Africa (Source: Harding et al., 2004).

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difficult within the region (Kociolek and Stoermer, 2001; Kelly et al., 2012; Bere, 2016a).

A further challenge that has been highlighted is the use of species data and ecological requirements of diatoms species between the northern and southern hemisphere. Questions remain concerning the range of ecological tolerances of widespread/introduced species due to various physico-chemical factors, distance and climate (Round, 1991). This view is supported by Mann and Droop (1996) and Kelly et al. (2012), who argued that a considerable number of diatoms are endemic and/or show a regionally restricted distribution due to specific physico-chemical factors at specific locations that determine this distribution, with geographic location being the determining factor in the distribution of diatom species and the composition of communities.

Besides the abovementioned logistical challenges, there is also a general perception that diatom biomonitoring is onerous and that the sample preparation is time consuming and requires high levels of expertise and taxonomic skills. In South Africa, unlike in other African countries, diatom ecologists are fortunate in that the majority of the taxonomic work had already been undertaken by Cholnoky (1950–1970) in Harding et al. (2004), with more work still to be done in unexplored environments. Benthic diatom taxonomy in the majority of sub-Saharan African countries, excluding countries such as South Africa, Sierra Leone, Gambia, Ghana and Malawi, warrants re-investigation as highlighted by the discovery of several new diatom species in Democratic Republic of Congo (DRC) (Cocquyt et al., 2013; Cocquyt and Taylor, 2015)and Zambia (Cocquyt et al. 2014; Taylor et al. 2014a, b). There is a strong reliance on the published diatom literature from European and American sources in the identification of species.

The absence of diatom experts and lack of necessary resources (e.g. microscopes, identification guides) in most African countries, represent significant obstacles in ensuring that diatom-based biomonitoring programmes are included as part of national policy, as is the case of South Africa which included diatoms in the River Health Programme and regular biomonitoring assessments. In Europe and the United States, all water systems are protected under one policy, such as the water quality European standards EN 14407:2004 and EN 13946:2003 and the EMAP-SW EPA/620/R-94/004F, which are constantly being amended in line with changing environments and research. In Africa, different regions can develop different policies that ensure that all aquatic ecosystems are properly conserved, managed and protected for future generations.

CONCLUSIONS AND RECOMMENDATIONS

Diatom-based biomonitoring programmes have been implemented with some success in Kenya, South Africa, Zambia and Zimbabwe. This approach has been incorporated into the national river health programme of South Africa (Dallas et al., 2010), now part of the National Aquatic Ecosystem Health Monitoring Programme (DWS, 2016);). It is anticipated that this approach will be adopted by several other African countries in the near future. The standardization of methodology has laid the foundation for the continued and meaningful collection and analysis of diatom samples in South Africa (Taylor et al., 2007a). It is anticipated to yield similar results in Kenya, Zambia, Zimbabwe and many other African countries that are currently in the process of standardizing their diatom methodology, although these protocols must consider endemic diatom taxa (see Bere (2016a), for Zimbabwean experiences).

In terms of diatom tolerances, ecological preferences and ecophysiology, much work still has to be done (Bate et al., 2002). All past research pertaining to African diatom taxonomy should be made readily accessible to all for use as a reference point, such as the work by Giffen (1963), Cholnoky (1968), Schoeman and Archibald (1977) and Taylor et al (2007c) highlighting the diatom flora of South Africa. On this point, the SAIAB National Diatom Collection is a commendable effort which making much of the grey literature readily accessible to other African researchers. The collection of diatom samples from different African countries, e.g. DRC, Zambia and Zimbabwe, for water quality determination should be complemented with sound taxonomical investigations to update knowledge of Africa's diatom flora (e.g. in Zambia, a new diatom species has been recently discovered (see Cocquyt et al., 2014; Taylor et al., 2014a, b) and also in DRC (see Cocquyt et al., 2013; Cocquyt and Taylor, 2015)). Cholnoky (1950–1970), and Giffen (1960–1980), amongst other authors, only produced diatom line diagrams which are open to misinterpretation, so the digitisation of the images of African and South African type specimens needs to be considered (Harding et al., 2004). Additionally, aquatic ecologists should work in conjunction with diatom taxonomists (see Kociolek and Stoermer, 2001). As this information becomes available it may then be resolved into numerical diatom indices. Finally attention should be paid to both the biology and ecology of diatoms occurring in moderate to high water quality environments, as several studies (e.g. Taylor et al., 2007; Bere et al., 2013; Mangedze et al., 2014; Bere 2016a) have highlighted that cosmopolitan species are found in a variety of habitats impacted by different types of pollutants.

One of the most important approaches that African and other countries around the world can adopt, which has also been observed with other biomonitoring methods such as macroinvertebrates (Chutter, 1998; Dickens and Graham, 2002; Metzeling et al., 2006), is to resort to intermediate diatom taxonomy, which is easier, less time consuming and requires less-skilled personnel. Development of a diatom biomonitoring method based on intermediate taxonomy, i.e., genus level, will make the process faster and easier. However, care must be taken to ensure that ecological information is not lost when taxonomic resolution is decreased, as this may compromise diatom model inferences. Several studies (e.g. Raunio and Soininen, 2007; Rimet and Bouchez, 2012; Keck et al., 2015) have highlighted that taxonomic resolution has little effect on diatom community structure description, suggesting that little ecological information is lost as a result of a decrease in diatom taxonomic resolution from species to genus level (see Kelly et al., 2016 for detailed information). However, Bowman and Bailey (1997) and Jones (2008) highlighted that information content increases with diatom taxonomic resolution. Taxonomic identifications become less certain at finer resolutions and data noise increases with increasing taxonomic resolution (Rimet and Bouchez, 2012). Therefore, we advocate for the use of genus level identification for water quality assessments and the development of appropriate indices based on genus level identification.

While the lack of capacity and baseline information on diatom community composition and ecological requirements represent significant hurdles, diatom biomonitoring potentially holds much promise for understanding the ecological functioning and informing the management of aquatic ecosystems in sub-Saharan Africa. Interdisciplinary research that will result in the union of environmental management, biogeography, conservation biology, diatom ecology and systematics could result in significantly more funding, if the relevance of diatom studies and biomonitoring is to be further developed. Results from such a multidisciplinary and integrative approach would also likely yield publications with a greater impact. There is a compelling need for diatom systematics research to be undertaken within multi-interdisciplinary projects, rather than focusing on the taxonomic identification, as such an approach will help in addressing challenging ecological problems.

African countries, like many European countries, should consider introducing ring tests to maintain the skills of the analysts, whereby they take part in identification of specific slides and pool the results to look for problem taxa and resolve prevailing issues (Hedden, 2010; Kelly, 2013). These tests can routinely be conducted, similar to the SASS training for macroinvertebrates which is conducted at approximately 6-monthly intervals by GroundTruth (GroundTruth, 2016). In this way, less experienced individuals can familiarize themselves with the various diatom taxa and acquire the necessary skills set to analyse diatom data, while at the same time providing an opportunity to recruit new researchers into the field. This approach might prevent the profession from collapse and enhance collaboration amongst diatom analysts and taxonomists from different regions of Africa. Across the world, identification is moving towards the use of molecular tools such that eventually identifying species using their basic morphology may become redundant. However, it is recognized that in many countries in Africa, the traditional identification techniques will still be required in the foreseeable future, as well as to interpret the research conducted by phylogeneticists and continue describing new species.

In conclusion, the use of diatom biomonitoring has importance in providing information relevant to common concerns about ecological condition and can be employed for short- and long-term monitoring of aquatic ecosystem function and health. Diatom monitoring programmes can provide results that are readily accessible to water managers and non-specialists. Regional examples from Kenya, South Africa, Zambia and Zimbabwe clearly indicate the importance and robustness of this protocol as a scientific biomonitoring tool (e.g. Stevenson, 2014).

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