Annual Research & Review in Biology
4(24): 4054-4074, 2014

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Use of Diatoms in River Health Assessment

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Authors' contributions

This work was carried out in collaboration between all authors. Authors XW and LL designed the study, wrote the protocol and wrote the first draft of the manuscript. Author BZ managed the analyses of the study. Author Li Li managed the literature searches. All authors read and approved the final manuscript.

Review Article

Received 11th June 2014
Accepted 5th July 2014
Published 24th July 2014

ABSTRACT

We review the use of diatoms in monitoring and assessment of river health in the world. First, we summarize the use of diatoms as indicators of nutritional status, acidification, and organic and metal pollution. We then examine some problems that have been associated with diatoms and indices that were used in different regions around the world: 1) incomplete taxonomy; 2) effects of natural geographic differences on diatom distributions (e.g., climate, lithology); 3) effects of natural site differences on diatom distribution and abundance (e.g., substrate, depth, chemistry); 4) differences in sampling, sample processing, and analytical methods; and 5) difficulties in finding minimally disturbed reference sites. Based on these problems, we present the different selections and the research progress of diatoms and indices used in monitoring and assessing river health around the world including the Americas, Europe, Africa, Asia, and Australia. We recommend that future studies and uses of diatoms focus on the following aspects: 1) improve the classification and identification of diatoms; 2) increase the use of diatom predictive indices to monitor and assess water quality; 3) develop global standard methods for sampling diatoms in streams, rivers, and lakes; and 4) apply hind-casting predictive models.

Keywords: Diatoms; diatom indices; river health; bioassessment; monitoring.

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1. INTRODUCTION

River systems are important ecosystems and provide water for many human uses. In the late 20^{th} century, coincident with rapid population and economic growth, local and global problems such as flow interruption, water pollution, and reduced biodiversity have altered the structure and function of rivers [1]. Because rivers are considered the most endangered ecosystems globally [2], it is urgent for humans to estimate river conditions and trends [3]. Physical, chemical and biological approaches are frequently considered as basic monitoring needs, because they can provide exhaustive information for proper water management [4]. But it is very difficult to monitor all possible physical and chemical variables because they are expensive, variable, and often poorly reflective of biological conditions. Therefore, biomonitoring has proven to be a necessary supplement to traditional chemical and physical monitoring [5].

Aquatic organisms, such as diatoms [6,7,8,9], can serve as bioindicators to integrate their total environment and their responses to complex sets of environmental conditions [10]. They make it possible to obtain an ecological overview of the current status of streams and rivers, and because they may attach to substrates, they integrate the real habitat conditions and respond more quickly to environmental changes than higher level organisms. This paper addresses the use of diatoms in the monitoring and assessment of water bodies, and examines problems associated with their use in different regions around the world. Based on problems revealed by recent studies, we suggest approaches and further research that may facilitate the use of diatom assemblages for bioassessment of river health.

2. WHY ARE DIATOMS USED AS INDICATORS IN MONITORING RIVERS?

2.1 Indication of Trophic Status

The species and abundances of diatoms are influenced strongly by the concentration and ratio of nitrogen and phosphorus in the water. Research on eutrophication in Florida, USA, has shown that changes in diatom biomass and diversity reflect changes in nitrogen or phosphorus concentration [11]. Studies on the relationships between the biomass and composition of benthic diatoms and environmental parameters in rivers indicate that the composition transformation of diatoms and the concentration of dissolved phosphorus are closely related to current velocity [12]. Bellinger et al. [13] pointed out that benthic diatoms could be used as indicators of eutrophication in tropical streams. Ponader et al. [14] reported that diatoms could be used as a routine tool to monitor and assess nitrogen and phosphorus concentrations in New Jersey streams and rivers. In other words, diatoms are excellent indicators of river trophic status (Table 1).

2.2 Indication of Acidified Water

Acid rain and acidic wastewater are major source of acidified water in rivers. Diatoms are very sensitive to water pH, and pH changes greatly influence the composition of diatom assemblages. Hustedt [15] sorted diatoms to the biotypes of alkalinity, basophilia, central, acidophilia and acidity according to the relationship of diatoms and water pH. Psenner and Schmidt [16] also indicated that the diatom assemblages distributed in acid rain areas indicated changes in pH, and that *Cyclotella bodanica* was acidophilic and generally observed in acidified water with greatest growth at pH 5. *Ulothrix* sp., is present below the source of mine drainage in St. Kevin Gulch, which is a headwater stream of the Rocky

Mountains of Colorado, receives acid mine drainage that maintains low pH [17]. In gently flowing waters, pH was an important factor influencing the survival of diatoms [18]. As a result, diatoms are good indicators of acidified rivers (Table 1).

2.3 Indicators of Organic and Metal Pollution

Heavy metal pollution can influence diatom survival and growth. Many studies on metal polluted rivers have shown that diatoms respond to environmental degradation at the assemblage level through shifts in dominant taxa and diversity patterns, as well as at the individual level [19]. For example, diatoms change in frustule morphology, size [20,21] and frustule deformations [22,23] in response to high metal concentrations. Changes in diatom assemblages relative to heavy metal pollution as reflected by multivariate analysis showed that diatom assemblages reflected heavy metal concentrations, and a pollution sensitivity index (PSI) reflected the metal pollution gradient. Cunningham et al. [24] also pointed out that the composition of benthic diatom assemblages could indicate heavy metal pollution of rivers. Diatom assemblages can be collected from artificial substrates, and used to assess the short-term effects of metal pollution on rivers [22]. Lamaia [25] reported that diatoms reflect the bioaccumulation amounts and rates of Cd and Pb, and also conducted real-time monitoring of heavy metal pollution in water.

Other physical and chemical parameters may also deform frustules, such as drought, high light intensity, UV radiation, salinity, nutrients, and other toxic compounds like cyanide, polycyclic aromatic hydrocarbons (PAH), and pesticides [19].

In addition, severe organic pollution can reduce diatom species richness, increase cell density, and reduce diversity and index values [26]. Denys [27] found that cell mass varied with water quality changes. Thus, diatom taxa can be used as indicators of various types of river pollution (Table 1).

Table 1. Partial diatoms used to indicate the status of water quality

	Species（author）	**Function**	**Reference**
Indication of trophic status	*Amphipleura pellucida* (Kützing)	Indication of low trophic state	[13,28,29]
	Cocconeis pediculus (Ehrenberg)		
	Cyclotella comta (Ehrenberg) Kützing		
	Cymbella affinis (Kützing)		
	Cymbella helvetica (Kützing)		
	Diatoma moniliformis (Kützing)		
	Encyonema caespitosum (Kützing)		
	Encyonema silesiacum (Bleisch in Rabenhorst) D.G. Mann		
	Encyonema microcephala (Grunow) Krammer		
	Eunotia bilunaris var. *mucophila* (Ehrenberg) Cleve		
	Fragilaria capucina (Desmazie`res)		
	Fragilaria capucina var. *vaucheriae* (Kützing) Lange-Bertalot		
	Fragilaria nanana (Lange-Bertalot)		
	Fragilaria pinnana (Ehrenberg)		

	Species（author）	Function	Reference
	Gomphonema angustum (Agardh)		
	Gomphonema angustatum (Kützing) Rabenhorst		
	Gomphonema minutum (Agardh)		
	Naviculadicta seminulum (Grunow) Lange-Bertalot		
	Nitzschia debilis (Arnott) Grunow		
	Nitzschia vermicularis (Kützing) Hantzsch		
	Pinnularia microstauron (Ehrenberg) Cleve		
	Pseudostaurosira brevistriata (Grunow) Williams & Round		
	Rhoicosphenia abbreviate (C.Agardh) Lange-Bertalot		
	Rhopalodia gibba (Ehrenberg) O. Mu¨ ller		
	Sellaphora laevissima (Kützing) D.G. Mann		
	Adlafia minuscule var. *muralis* (Grunow) Lange-Bertalot	Indication of eutrophic state	
	Amphora veneta (Kützing)		
	Anomoeoneis sphaerophora (Ehrenberg) Pfitzer		
	Craticula cuspidate (Kützing) Mann		
	Craticula halophila (Grunow ex van Heurck) Mann		
	Cymbella pusilla (Grunow)		
	Eolimna subminuscula (Manguin) Lange-Bertalot & Metzeltin		
	Fallacia pygmaea (Kützing) Stickle & Mann		
	Fragilaria ulna (Nitzsch) Lange-Bertalot		
	Gomphonema pseudoaugur (Lange-Bertalot)		
	Navicula cincta (Ehrenberg) Ralfs		
	Navicula cryptotenella (Lange-Bertalot)		
	Nitzschia clausii (Hantzsch)		
	Nitzschia communis (Rabenhorst)		
	Nitzschia constricta (Kützing) *Ralfs*		
	Nitzschia supralitorea (Lange-Bertalot)		
	Surirella brebissonii (Krammer & Lange-Bertalot)		
	Surirella ovalis (Brébisson)		
	Surirella peisonis (Pantocsek)		
	Tryblionella hungarica (Grunow)D.G.Mann		
	Gomphonema parvulum (Kützing) Kützing		

	Species（author）	Function	Reference
Indication of acidified water	*Cyclotella bodanica Eul* (Kützing)	Dominant species in acid water	[16,17]
	Eunotia paludosa var. trinacria (Grunow)		
	Eunotia tenella (Grunow)		
	Eunotia sudetica (Agardh) Cleve		
	Pinnularia subcapitata (Grunow)		
	Achnanthes kryophila (J.B Petersen)		
	Neidium affine (Ehrenberg) Pfitz.		
	Achnanthes minutissima (Kützing) Czarneczki		
	Eunotia septentrionalis (Qstrup)		
	Nitzschia capitellata (Hust.)		
	Nitzschia communis (Rabenh.)		
	Nitzschia pusilla (Grunow)		
	Pinnularia acoricola (Hust.)		
	Pinnularia obscura (Krasske)		
	Pinnularia braunii var. amphicephala (A.Mayer) Hust.		
	Pinnularia subcapitata (Agardh) Cleve		
	Pinnularia terminitina (Ehrenberg) R.M.Patrick		
	Eunotia exigua (Brébisson) Rabenh.		
Indication of pollutant	*Fragilaria capucina* (Desm.)	Indication of copper	[19,29,30]
	Synedra ulna (Nitzsch.) Ehrenberg	Indication of zinc	
	Cymatopleura solea (Brébisson & Godey) W.Sm.	Indication of hydroxybenzene	
	Synedra ulna (Nitzsch.) Ehrenberg	Indication of hydrargyrum	
	Amphora libyca (Ehrenberg)	Indication of sensitivity	
	Cymbella amphicephala (Nägeli)		
	Cymbella silesiaca (Bleisch)		
	Cymbella sinuate (Gregory)		
	Fragilaria pinnata (Ehrenberg)		
	Gomphonema olivaceum (Hornemann) Brébisson var. olivaceum		
	Navicula radiosa (Kützing)		
	Nitzschia fonticola (Grunow non sensu Hustedt)		
	Nitzschia gracilis (Hantzsch)		
	Nitzschia lacuum (Lange-Bertalot)		
	Nitzschia recta (Hantzsch)		
	Stephanodiscus minutulus (Kützing) Cleve & Möller		
	Achnanthes delicatula (Kützing) Grunow	Indication of middle tolerance	
	Achnanthes lanceolata (Brébisson) Grunow		
	Cocconeis placentula (Ehrenberg)		
	Cyclotella meneghiniana (Kützing)		
	Cymbella caespitosa (Kützing) Burn		

	Species（author）	Function	Reference
	Diatoma tenuis (Kützing)		
	Diatoma vulgaris (Bory)		
	Meridion circulare (Gréville) Agardh		
	Navicula capitatoradiata (Germain)		
	Navicula cryptocephala (Kützing)		
	Navicula cryptotenella (Lange-Bertalot)		
	Navicula gregaria (Donkin)		
	Navicula lanceolata (Agardh) Ehrenberg		
	Navicula reichardtiana (Lange-Bertalot)		
	Navicula tripunctata (O.F.Müller) Bory		
	Navicula trivialis (Lange-Bertalot)		
	Nitzschia acicularis (Kützing) W. Smith		
	Nitzschia archibaldi (Lange-Bertalot)		
	Nitzschia dissipata (Kützing) Grunow		
	Nitzschia frustulum (Kützing) Grunow		
	Nitzschia graciliformis (Lange-Bertalot & Simonsen)		
	Nitzschia heufleriana (Grunow)		
	Nitzschia inconspicua (Grunow)		
	Nitzschia linearis (Agardh) W. Smith		
	Nitzschia sociabilis (Hustedt)		
	Stephanodiscus hantzschii (Grunow)		
	Gomphonema parvulum (Kützing) Kützing var. parvulum	Indication of high tolerance	
	Navicula saprophila (Lange-Bertalot & Bonik)		
	Navicula atomus (Kützing) Grunow		
	Navicula minima (Grunow)		
	Nitzschia palea (Kützing) W. Smith		

3. INDICATORS OF GENERAL RIVER HEALTH ASSESSMENT

Based on the indicator functions [31] that have been associated with diatoms used throughout the world, researchers combine diatoms and environmental parameters through use of statistical means to develop mathematic models, improving the effectiveness of water quality monitoring with diatoms. In recent years, integrative bioassessment systems have been established by using diatom indices that were widely used in river health assessment around the world, including the Americas, Europe, Africa, Asia, and Australia (Table 2).

3.1 North America

In North America, diatoms and indices are mostly used in the United States and Canada. There has been a long history regarding river health assessment using diatoms in the United States and diatom sampling is a routine component of biomonitoring and bioassessment in the United States. Patrick [32] investigated the eastern watershed of United States and used diatoms as one monitoring project of water quality assessment with her colleague, results showed that diatoms represented well applicability in river health assessment. As time went on, more and more diatom assemblages and diatom indices have been used in the monitoring and assessment of river health. Stevenson [33] investigated changes of relative richness and biodiversity of diatom assemblages influenced by contamination in the Sandusky River using the theories of diatom community dynamics. His results showed that diatom assemblage indices were applicable for assessing the ecological quality of streams without focusing on specific indicator taxa. In the northern United States, monitoring with multivariate analysis may be traced back to the late 20th century [34]. Sophia [35] developed a new biological index, DMA (diatom model affinity), based on many investigations to assess river health. DMA provides an assessment of water quality by calculating percent similarity with a model community that serves as a reference standard. The Kentucky Department of Environmental Protection developed a diatom biological index (DBI) to assess the biological integrity of Kentucky waters; the DBI consists of six metrics: diatom taxa richness, Shannon diversity, a pollution tolerance index (PTI), a siltation index, *Fragilaria* richness, and *Cymbella* richness [36]. Researchers in Idaho found that diatoms were the dominant species of periphyton, so they developed a multimetric index for assessing river health, making diatom, fish and macroinvertebrate assemblages important tools to estimate river community health [37]. To calculate the periphyton index of biological integrity (P-IBI), Hill [38] conducted systematic analyses of species abundance, dominant species, Chl*a* content, biomass, and alkaline phosphatase of diatoms after collecting basic environmental parameters for 272 streams in the eastern United States. Potapova et al. [39] monitored eutrophication status of United States Rivers by using diatom indices on data collected by the United States Geological Survey; the results indicated higher water quality than in Europe.

In Florida, USA, 11 wetlands were sampled in once each in the dry and wet seasons over a 5-month period. The results showed that dry season sites had significantly higher diatom genus and species richness, and non-metric multidimensional scaling and multiple response permutation process analyses indicated no significant wet/dry grouping of species or genus level abundance data [40]. Wachnicka et al. [41] investigated the diatom ecology and distribution in Biscayne Bay, Florida (USA), and found that diatom assemblages differed between nearshore and offshore locations, especially during the wet season when salinity and nutrient gradients were steepest. Planktonic and periphytic diatom assemblages were investigated as potential biological indicators of ecological conditions in the Ohio, Missouri and Upper Mississippi rivers. The results indicated (1) the value of diatoms for assessing landscape stressors of large rivers, (2) traditional water quality conditions, and (3) the usefulness of both planktonic and periphytic diatom assemblages as bioindicators of river condition and for providing unique stressor response information [42].

In a word, diatoms and diatom indices have been more and more popularly used in the bioassessment of river health in United States. We can see the importance of diatoms among in aquatic organisms.

In Canada, researchers on great rivers reported that diatoms could monitor organic pollution and eutrophication [29]. For example, studies in the streams and rivers of southern Québec showed that benthic diatoms provided an integrated measurement of water quality and provided a useful addition to physico-chemical water quality monitoring [72]. Lavoie et al. (2006) [72] developed a diatom-based index for the biological assessment of eastern Canadian rivers. The Eastern Canadian Diatom Index (IDEC) integrates the effects of multiple stressors on streams and provides information about the “distance” from the nonimpacted state. Later, Lavoie et al. [73] compared stream condition in Québec through use of six diatom-based indices from Europe (TDI, SPI, IBD, SLA) and North America (IBI, IDEC); the results confirmed that most of the common riverine taxa have similar ecological preferences throughout Europe and North America. Their comparison illustrated the similarity of the results and robustness of diatom-based monitoring regardless of the indices used. Following the continuous in-depth study, Grenier et al. [70] proposed a remodeling of five classes of the IDEC by introducing ecologically meaningful thresholds, reducing subjectivity in the determination of the number and range (widths) of classes, and developing a new approach that uses biotypes issued from a classification technique (Self-Organizing Maps) to determine thresholds among integrity classes of the IDEC.

Table 2. Diatom indices widely used in river health assessment

Diatom indices	Discription	Reference
Percent Community Similarity of Diatoms (PSc)	This index is used to compare control and test sites, or average community of a group of control or reference sites with a test site. Percent community similarity values range from 0 (no similarity) to 100%.	[43]
Simple Autecological Index (SAI)	This index is used to characterize different diatom species along an environmental (stressor) gradient and infer environmental conditions (EC) and effect on the periphyton assemblage.	[44]
Descy Index (DI)	The first diatom index developed by Descy in 1979.	[45]
Pollution Tolerance Index for Diatoms (PTI)	This index is used to distinguish categories of diatoms according to their tolerance to increased pollution, with species assigned a value of 1 for most tolerant taxa (e.g., *Nitzschia palea* or *Gomphonema parvulum*) to 3 for relatively sensitive species.	[46]
Specific Pollution Sensitivity Index (SPI)	Bioassessment of water quality via calculating the proportion of specific pollution sensitive species.	[47]
Diatom Assemblage Index for Organic Pollution (DAIpo)	Calculates the relative abundance of eusaprobic and eurysaprobic species to assess the degree of polluted water.	[48]
Sládeèek Index (SLA)	Bioassessment of water quality via calculating the proportion of saprobic diatom species.	[49]
Index of Leclercq & Maquet (ILM)	This index is used to indicate organic pollution and assess water quality. Derived from Sladecek's method, Leclercq and Maquet proposed other values for the "saprobic valencies" (s) and for the "indicator values" (v).	[50]
Schiefele & Schreiner index (SHE)	Calculates the relative abundances of each pollution group	[51,52]
Generic Diatom Index (GDI)	This index is the ratio of abundance of *Achnanthes, Cocconeis* and *Cymbella*, to that of *Cyclotella, Melosira* and *Nitzschia* to measure diatom assemblage changes.	[53,54]
Commission of Economic Community Index (CEC)	This index is correlated with parameters related to organic pollution, ionic strength, and eutrophication and seems to give a more realistic estimation of water quality.	[55]

Diatom indices	**Discription**	**Reference**
Percent Motile Diatoms (PMD)	This is a siltation index, expressed as the relative proportion of *Navicula* + *Nitzschia* + *Surirella*. The three genera are able to move towards the surface if they are covered by silt; their abundance is thought to reflect the amount and frequency of siltation. Relative abundances of *Gyrosigma*, *Cylindrotheca*, and other motile diatoms also may be added to this index.	[56]
Trophic Diatom Index (TDI)	This index is used to monitor the trophic status of rivers based on diatom composition. TDI=(WMS×25)–25, WMS=Weighted mean sensitivity,calculated as: WMS=$\sum a_j v\, i_j / \sum a_j v_j$, where a_j = abundance (proportion) of speciesj in sample, s_f= pollutionsensitivity(l–5) of speciesj and V_j= indicator value (l–3). s_j was derived empirically.	[57]
Biological Diatom Index (BDI)	This index is based on a list of 209 key species showing different pollution sensitivities. The pollution sensitivity, or ‘‘ecological profile’’, is determined through the species presence probability values along a seven quality classes gradient.	[58,59,60]
Rott saprobic index (ROT)	This index is an improved saprobic index based on the Sládeèek Index; some saprobic values and indicator values have been changed.	[61]
Percent live diatoms (PDI)	This index is used to indicate the health of the diatom assemblage. Low percent live diatoms could be due to heavy sedimentation and/or relatively old algal assemblages with high algal biomass on substrates.	[62]
Percent Aberrant Diatoms (PAD)	PAD is the percent of diatoms in a sample that have anomalies in striae patterns or frustule shape (e.g, long cells that are bent or cells with indentations). This index has been positively correlated with heavy metal contamination in streams.	[63]
Shannon Diversity (for diatoms)	It is a function of both the number of species in a sample and the distribution evenness of individuals of those species.	[64]
Percent *Achnanthes minutissima*	This index is used in bioassessment, the quartiles of this index from a population of sites has been used to establish judgment criteria, e.g., 0-25% = no disturbance, 25-50% = minor disturbance, 50-75% = moderate disturbance, and 75-100% = severe disturbance.	[64]
Percent Sensitive Diatoms (PSD)	This index is the sum of the relative abundances of all intolerant species. This	[64]

Diatom indices	Discription	Reference
	index is especially important in smaller-order streams where primary productivity may be naturally low, causing many other indices to underestimate water quality.	
Diatom Model Affinity (DMA)	DMA provides an assessment of water quality by the calculation of percent similarity to a model community that can be viewed as a reference standard. High similarity to the model indicates assemblages that are minimally disturbed, while lower similarity suggests water quality problems.	[35,65]
Pampean Diatom Index (PDI&IDP)	The index integrates organic pollution and eutrophication and can be applied for monitoring the biological quality of rivers and streams in the Pampean plain.	[66]
Eutrophication Pollution Index using diatoms (EPI)	This index was developed for Appenine watercourses, based on the sensitivity of diatoms to organic pollution, mineralization of water, and chloride.	[67]
Relative Abundance of Diatom Species (RAD)	High species richness is assumed to indicate high biotic integrity because many species are adapted to the conditions present in the habitat. Species richness is predicted to decrease with increasing pollution because many species are stressed.	[68]
Eastern Canadian Diatom Index (IDEC)	This index is based on correspondence analysis (CA) to develop a chemistry-free index, where the position of the sites along the gradient of maximum variance is strictly determined by diatom assemblage structure and therefore is dependent on measured environmental variables.	[69,70]
Diatom Species Index for Australian Rivers (DSLAR)	This index is used as a broad-scale indicator of human influences on Australian rivers, especially the effects of agricultural and urban land use, and also for impact studies at local scales.	[71]

3.2 South America

In South America, diatoms and indices are mostly used in Argentina and Brazil. In Argentina, assessing water quality with diatoms became popular in the late 20th century. Gomez [74] used epipelic diatom assemblages to evaluate water quality in the Matanza-Ria-Chuelo River Basin, and the results showed that the assemblage was dominated by pollution-tolerant species as anthropogenic disturbances increased. Gomez and Licursi [66] found that benthic diatoms were suitable for monitoring organic pollutants in Pampean rivers and developed the Pampean diatom index (PDI) to assess river health. Hassan et al. [75] assessed the spatial variation of diatom assemblages in two representative estuaries of Argentina to gather ecological information for paleoecological reconstructions in the region.

Then Hassan et al. [76] studied the relationship between benthic diatom assemblages and environmental variables in three northeastern Argentina estuaries via multivariate analyses. Their research showed that diatoms and diatom indices were good tools for monitoring river health.

In Brazil, monitoring and assessing river health with diatoms became common in the early 21st century. In 2004, Lobo et al. [77] used epilithic diatom assemblages as bioindicators to evaluate the water quality of two urban streams, Condor and Capivara, in Porto Alegre, Rio Grande do Sul, and the results showed that, *Mayamaea atomus*, *Amphora montana*, *Sellaphora pupula* and *Cyclotella meneghiniana* were extremely abundant under such conditions. Then, diatoms were used successfully as bioindicators of water quality in the Gravataí River, Rio Grande do Sul [78] and other rivers near São Carlos, Sao Paulo [79]. In 2012, Bere and Tundisi [80] used the PDI developed in Argentina to assess streams around São Carlos, Sao Paulo; the results showed that the PDI can be applied to non-epipelic and non-Pampean diatom assemblages.

3.3 Europe

Benthic diatoms are also widely used in assessing the health status of European streams. Researchers use different methods to sample diatoms and analyze data. Prygiel and Coste [81] used diatom indices (e.g. specific pollution sensitivity index (PSI), generic diatom index (GDI), the Commission of Economical Community Index (CEC), and so on.) to estimate the status of water quality in the Artois-Picardie Basin (France), and the results showed that the diatom indices satisfactorily assessed organic pollution levels and water quality degradation. In 2000, the European Water Framework Directive recommended using diatoms as biological indicators to confirm nutritient levels in decision-making regarding water environment rehabilitation. From then on, diatoms became routine programs in the state biological monitoring and were used to support water quality law and regulatory criteria. Researchers developed and used Zelinka and Marvan functions along with diatoms to monitor eutrophication status, adequately considering the sampling errors and changes in assemblage taxa. Based on this approach, the biological diatom index (BDI) was adopted as a standard method and field and laboratory manuals were developed [59]. The manuals included field sampling description, laboratory analyses, species classification and identification, data analyses, and BDI score calculation based on assemblage composition, relative richness, and physical-chemical parameters. The BDI is now used to assess ecological quality, monitor temporal and spatial variation at the river basin scale, and in applied research projects [60,82,83,84]. Rott et al. [85] pointed out that we should consider the applicability of assessment indices and choose the indices according to water pollution status when necessary. Nine diatom indices were studied, and the results showed that the BDI、GDI、ILM, and SLA had intermediate sensitivities to water pollution, and the CEC、EPI、ROT、SPI、and TDI had higher sensitivities. Rimet et al. [82] found that diatom indices were not suitable for all kinds of contamination, being sensitive only under their optimum ranges. Researchers in Denmark used benthic diatoms to assess watershed quality [86]. Tison et al. [87] developed an ecological distance index (EDI) to collect diatom data from a pilot watershed, and the results demonstrated a good correlation between the EDI and the SPSI, which indicated that the EDI was a valuable indicator of ecological status to account for ecoregional differences. In France, diatom indices were considered as standard means to assess the status of river health [60]. Researchers evaluated European diatom trophic indices through use of the STAR (Standardisations of River Classifications) diatom database, a large data set from European running waters, to test the application of trophic classifications in water quality assessment. The results showed that differences between trophic indices also led to a significant variation in water quality assessment, so trophic indices should be applied with caution [88]. Delgado et al. [89] used diatom assemblages as ecological status indicators in Mediterranean temporary streams on the Balearic Islands, Spain. A diatom multimetric index (DIATMIB) was developed that combined the following three metrics: abundance of sensitive taxa, abundance of tolerant taxa, and chlorophyll a. The study validated the application of a diatom multimetric index as an appropriate approach for classify the ecological status of temporary streams as a function of structural changes in diatom assemblages.

3.4 Africa

In Africa, many researchers also use diatoms to assess river health. Archibald (1992) [90] examined the diversity of diatom associations from some South African rivers in relation to water quality. He found that, diversity was regarded as a dubious and sometimes misleading parameter of water quality. The specific composition of the assemblages and the autecology of the component species, particularly the dominants, were preferable criteria for assessing water quality via diatom assemblages. Similar research was conducted in other South African rivers [91,92]. Although diatoms were used in assessing river health earlier in Africa, they were not commonly used until the early 21st century. For example, Bate et al. (2004) [31] found that diatoms were good indicators of total dissolved solids in rivers. Taylor et al. [93] evaluated diatom-based indices in the Vaal and Wilge Rivers, South Africa. Their results indicated that the tested diatom indices in general were most highly correlated with average chemical data for a one-month period, six weeks prior to biological sampling. The Biological Diatom Index showed the strongest relationship to general water quality, whereas the Eutrophication and Pollution Index showed the strongest relationship to dissolved inorganic phosphorus. Beyene et al. [94] compared diatoms and macroinvertebrates as indicators of severe water pollution in Addis Ababa, Ethiopia. Based on assemblage metrics and multivariate analysis results, the results showed that diatoms indicated a gradient of pollution more reliably than macroinvertebrates. Diatoms were good indicators of pollution levels among heavily impacted sites where macroinvertebrates were completely absent or less diverse, and powerful bioindicators for monitoring urban-impacted and seriously stressed rivers. They also found that diatoms were useful indicators of pollution gradients and impacts of specific pollution sources. Chaïb and Tison-Rosebery [95] analyzed 118 benthic diatom taxa used in water quality assessment and the application of a biological diatom index in the Kebir-East Wadi, Algeria; they concluded that a specific diatom index should be developed because of the particular geochemical conditions of that wadi.

3.5 Asia and Australia

Diatoms and indices are widely used to assess river health in Asia. Wu [96] studied a two-year change of diatom assemblages in relation to water pollution in the Hsin-Dien River, China. As water pollution increased, the species richness and diversity of diatom assemblages decreased, whereas redundancy increased. A similar study was carried out in Japan, and Lobo et al. [97] found that the species richness of diatom assemblages tended to be higher in the intermediate range of water pollution, and the diatom assemblage response to environmental change could be observed in species compositional variation. Diatoms were also used as indicators of stream quality in the Kathmandu Valley and Middle Hills of Nepal and India [98]. In 2006, Duong et al. [99] studied the impact of urban pollution from the Hanoi area on benthic diatom assemblages collected from the Red, Nhue, and Tolich rivers (Vietnam), and used two diatom indices, SPI and DAIpo, to evaluate water quality. The assessment results indicated that the Tolich River has the lowest values because of high pollution levels. Atazadeh et al. [100] found that, the sensitivity of the TDI and its component metrics to environmental stressors supported the use of this index for monitoring ecological conditions in streams in Iran, and to aid diagnosis of the cause of site impairment. Wu et al. [101] investigated benthic diatom communities of 23 run-of-river dams in a Chinese river during the dry season and selected four metrics from 110 diatom attributes to construct a diatom-based index of biotic integrity (D-IBI); the test results and metrics of D-IBI using an independent testing data set indicated significant differences between reference and impaired sites.

Studies of diatoms appeared during the end of the 20th century in southwestern Australia, in a stream-rich area with relatively undisturbed streams and in highly disturbed Perth streams [102]. The results showed that diatom taxa distributions were correlated with pH, conductivity, riparian forest width, water depth, current velocity, and riparian degradation, and therefore could be used in assessing river health. Diatom indices are useful for explaining the condition of rivers and in the Australian river assessment system (AusRIVAS). Researchers developed a diatom assemblage predictive model similar to the river invertebrate prediction and classification system (RIVPACS) to assess and monitor the ecological health of rivers nationwide [103]. Chessman et al. [71] used the diatom index for Australian rivers (DIAR) to assess river status, and the results showed that the diatom species index for Australian rivers (DSIAR) was strongly and significantly correlated with measures of catchment urbanization for streams in the eastern suburbs of Melbourne, Victoria. DSIAR scores across southeastern Australia had little relationship to the latitude, longitude or altitude of sampling sites, which means that DSIAR was slightly affected by macro-geographical position. In addition, DSIAR scores vary little among small-scale hydraulic environments within a site and appeared to have potential as a broad-scale indicator of human influences on Australian rivers, including the effects of agricultural and urban land use, as well as local-scale impact studies. Haese et al. [104] measured benthic nutrients, gas fluxes, water column properties, and sediment properties in an estuary of southeastern Australia. Their results showed that molar ratios of dissolved inorganic carbon to silica benthic fluxes were equal to the molar composition of diatoms, indicating that diatoms preferentially sink and deliver the most labile organic matter fraction to the sediment.

Globally, river health monitoring and assessments based on diatoms and diatom indices have become increasingly important, and they are key indicators for the bioassessment of aquatic ecosystems.

4. LIMITATION OF DIATOMS IN RIVER HEALTH BIOASSESSMENT AND RESEARCH RECOMMENDATIONS

Although diatoms have been widely used in monitoring the trophic status of water, acidified water, and various water pollutants, four major problems remain in using diatoms for river health assessment: 1) The classification and identification system has not been completed globally. There are perhaps ten million diatom species in the world and they are distributed diffusely [105]; however, only ten thousand of them have been identified, some have disappeared because of pollution, and new species are being identified. Researchers are continuously modifying and reclassifying current diatom species, so diatom species listed in most current diatom sets are not perfect. Further research is needed in the identification and classification of species, with the goal of globally applicable keys. 2) Climate change and natural environmental variability confounds the usefulness of many diatom applications. For example, natural temporal and spatial differences in temperature, current velocity, pH, dissolved oxygen, salinity, water depth, insolation, and substrates cause variations in diatom assemblage composition. However, the growth of diatoms is also influenced by parameters of chemistry, hydrology and so on, increasing the random errors of sampling and calculation results of metrics. Such physical and chemical variables observably influence the growth, propagation, and distribution of diatoms, thereby hindering long-term and continuous monitoring and assessment of water quality. Additional research is needed to calibrate expected species occurrences and abundances, metric values, and index scores along those natural environmental gradients that co-vary with anthropogenic disturbances. Besides that, the water quality bioassessment could be carried out by the integrated index based on multiplicate indices [106,107,108], or using more than one assemblage indices so as to decrease the influences of climate change and natural environmental variability on the credibility of diatom applications. 3) Minimally-disturbed reference sites are difficult to find in extensively and intensively altered ecoregions, making it equally difficult to predict expected diatom assemblage composition in the absence of disturbance. Research involving hind-casting predictive models incorporating no or very little anthropogenic disturbance may provide a means of determining reference conditions via statistical extrapolation [109]. 4) Natural differences in water bodies, together with researcher preferences, have induced a diverse set of sampling, sample processing, and indexing approaches [64,105]. Such differences influence the diatom species and abundances occurring in the samples, thereby confounding observed diatom differences with sampling error. Studies comparing alternative sampling, sample processing, and indexing methods are needed with the goal of developing standard methods for diatom assemblages, just as we have developed standard methods for chemical sampling and analyses and as have been proposed for fish, macroinvertebrates, and algae [110,111].

5. CONCLUSION

In this study, the use of diatoms as indicators of nutritional status, acidification, and organic and metal pollution were summarized. As seen in this study there are some problems that have been associated with diatoms and indices that were used in different regions around the world. Based on these problems, the different selections and the research progress of diatoms and indices used in monitoring and assessing river health around the world including the Americas, Europe, Africa, Asia, and Australia were presented. Finally, future studies and uses of diatoms focus on the following aspects: 1) improve the classification and identification of diatoms; 2) increase the use of diatom predictive indices to monitor and assess water quality; 3) develop global standard methods for sampling diatoms in streams, rivers, and lakes; and 4) apply hind-casting predictive models, were recommended by the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Poff NLR, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. The natural flow regime, a paradigm for river conservation and restoration. Bioscience. 1997;47:769-784.

2. Saunders DL, Meeuwig JJ, Vincent ACJ. Freshwater protected areas: Strategies for Conservation. Conserv Biol. 2002;16:30-41.
3. Rosenberg DM, Resh VH, (Eds). Freshwater biomonitoring and benthic macroinvertebrates. Chapman and Hall, New York; 1993.
4. Metcalfe JL. Biological water quality assessment of running waters based on macroinvertebrate communities: History and present status in Europe. Environ Pollut. 1989;60:101-139.
5. Soininen J, Könönen K. Comparative study of monitoring South-Finnish Rivers and streams using macroinvertebrates and benthic diatom community structure. Aquat Ecol. 2004;38:63-75.
6. Patrick R. Use of algae, especially diatoms, in the assessment of water quality. In: Cairns JJr, Dickson KL, (Eds). Biological methods for the assessment of water quality. J Am Soc Test Mater Phila. 1973;76-95.
7. Stevenson RJ, Lowe RL. Sampling and interpretation of algal patterns for water quality assessments, In: Isorn BG, (Ed.). Rationale for sampling and interpretation of ecological data in the assessment of freshwater ecosystems. J Am Soc Test Mater, Phila. 1986;118-149.
8. Lowe RL, Pan Y. Benthic algal communities as biological indicators. In: Stevenson RJ, Bothwell ML, Lowe RL, (Eds). Algal ecology: freshwater benthic ecosystems. Academic Press, San Diego. 1996;705-739.
9. Stevenson RJ, Pan YD. Assessing environmental conditions in rivers and streams with diatoms. In: Stoermer EF, Smol JP, (Eds). The diatoms: Applications for the environmental and earth sciences. Cambridge University Press, Cambridge. 2001;11-40.
10. Worf DL. Biological monitoring for environmental effects. Lexington Books, Toronto. Archibald R E M. Diversity in some South African diatom associations and its relation to water quality. Water Res. 1972;6:1229-1238.
11. Gaiser EE, Childrens DL, Jones RD, Richards JH, Scinto LJ, Trexler JC. Periphyton responses to eutrophication in the Florida Everglades: Cross-system patterns of structural and compositional change. Limnol Oceanogr. 2006;51:617-630.
12. Kingsley M, Pick FR, Hamilton PB. Periphyton biomass and composition of British Columbia salmonid rivers in relation to nutrient and discharge levels. P Int Assoc Theor Appl Limnol. 2006;29:1389-1398.
13. Bellinger BJ, Cocquyt C, O'reilly CM. Benthic diatoms as indicators of eutrophication in tropical streams. Hydrobiol. 2006;573:75-87.
14. Ponader KC, Charles DF, Belton TJ. Diatom-based TP and TN inference models and indices for monitoring nutrient enrichment of New Jersey streams. Ecol Indicators. 2007;7:79-93.
15. Hustedt SH. The non-concept of species diversity: A critique and alternative parameters. Ecol. 1971;52:577-586.
16. Psenner R, Schmidt R. Chimate-driven pH: control of remote alpine lakes and effects of acid deposition. Nature. 1992;356:781-783.
17. Niyogi DK, McKnight DM, Lewis WM. Influences of water and substrate quality for periphyton in a montane stream affected by acid mine drainage. Limnol Oceanogr. 1999;44:804-809.

18. Carpenter KD, Waite IR. Relations of habitatspecific algal assemblages to land-use and water chemistry in the Willamette basin, Oregon. Environ Monit Assess. 2000;64:247-257.
19. Silva EF, Almeida SFP, Nunes ML, Luis AT, Borg F, Hedlund M, De Sa CM, Patinha C, Teixeira P. Heavy metal pollution downstream the abandoned Coval da Mó mine (Portugal) and associated effects on epilithic diatom communities. Sci Total Environ. 2009;407:5620-5636.
20. Gensemer RW. Role of aluminium and growth rate on changes in cell size and silica content of silica-limited populations of *Asterionella ralfsii* var. Americana (*Bacillariophyceae*). J Phycol. 1990;26:250-258.
21. Cattaneo A, Asioli A, Comoli P. Organisms response in a chronically polluted lake supports hypothesized link between stress and size. Limnol Oceanogr. 1998;43:1938-1943.
22. Gold C, Feurtet-Mazel A, Coste M, Boudou A. Impacts of Cd and Zn on the development of periphytic diatom communities in artificial streams located along a river pollution gradient. Arch Environ Con Tox. 2003;44:189-197.
23. Cattaneo A, Couillard Y, Wunsam S, Courcelles M. Diatom taxonomic and morphological changes as indicators of metal pollution and recovery in Lac Dufault (Québec, Canada). J Paleolimnol. 2004;32:163-175.
24. Cunningham L, Raymond B, Snape I, Riddle MJ. Benthic diatom communities as indicators of anthropogenic metal contamination at Casey Station, Antarctica. J Paleolimnol. 2005;33:499-513.
25. Lamaia C, Kruatrachuea M. Toxicity and Accumulation of Lead and Cadmium in the Filamentous Green Alga *Ladophora fracta*: A laboratory study. Science Asia. 2005;31:121-127.
26. Chen F, Wang MS, Deng HP, Liu CK. The influence of organic pollution on diversity of diatom in nanchong section of Jialing River. Journal of Southwest China Normal University (Natural Science Edition). 2008;33:44-47.
27. Denys L. Environmental changes in man-made coastal dune pools since 1850 as indicated by sedimentary and epiphytic diatom assemblages (Belgium). Mar. Freshwater Res. 2003;13:191-211.
28. Kova´cs CS, Buczko K, Hajnal E. Epiphytic, littoral diatoms as bioindicators of shallow lake trophic status: Trophic Diatom Index for Lakes (TDIL) developed in Hungary. Hydrobiol. 2007;589:141-154.
29. Rott E, Duthie HC, Pipp E. Monitoring organic pollution and eutrophication in the Grand River, Ontario, by means of diatoms. Can J Fish Aquat Sci. 1998;55:1443-1453.
30. Gu YJ, Live YH. The vertical distribution of diatoms in the sediments and water quality change of Suzhou Creek. Acta Ecol Sinica. 2006;26:3617-3623.
31. Bate G, Smailes P, Adams J. A water quality index for use with diatoms in the assessment of rivers. Water SA. 2004;30:493-498.
32. Patrick R. A study of the numbers and kinds of species found in rivers in eastern United States. P Acad Nat Sci Phila. 1961;113:215-235.
33. Stevenson RJ. Epilithic and epipelic diatoms in the Sandusky River, with emphasis on species diversity and water pollution. Hydrobiol. 1984;114:161-175.

34. Charles D. Use of algae for monitoring rivers in the United States: Some examples. In use of algae for monitoring rivers II. Edited by Whitton BA, Rott E. Institute of Botany, University of Innsbruck, Innsbruck, Austria. 1996;109-118.
35. Sophia IP. Spatial paradigms of lotic diatom distribution: A landscape ecology perspective. J Phycol. 2001;37:370-378.
36. Kentucky DOW. Methods for assessing biological integrity of surface waters in Kentucky. Division of Water, Water Quality Branch, Natural Resource and Environmental Protection Cabinet, Frankfort, Kentucky; 2002.
37. Fore LS, Grafe C. Using diatoms to assess the biological condition of large rivers in Idaho (USA.). Freshwater Biol. 2002;47:2015-2037.
38. Hill BH. Assessment of streams of the eastern United States using a periphyton index of biotic integrity. Ecol Indicators. 2003;2:325-338.
39. Potapova M, Charles DF. Diatom metrics for monitoring eutrophication in rivers of the United States. Ecol Indicators. 2007;7:48-70.
40. Lane CR, Reiss KC, DeCelles S, Brown MT. Benthic diatom composition in isolated forested wetlands subject to drying: Implications for monitoring and assessment. Ecol Indicators. 2009;9:1121-1128.
41. Wachnicka A, Gaiser E, Boyer J. Ecology and distribution of diatoms in Biscayne Bay, Florida (USA): Implications for bioassessment and paleoenvironmental studies. Ecol Indicators. 2011;11:622-632.
42. Kireta AR, Reavie ED, Sgro GV, Angradi TR, Bolgrien DW, Hill BH, Jicha TM. Planktonic and periphytic diatoms as indicators of stress on great rivers of the United States: Testing water quality and disturbance models. Ecol Indicators. 2012;13:222-231.
43. Whittaker RH, Fairbanks CW. A study of plankton copepod communities in the Columbia basin, Southeastern Washington. Ecol. 1958;39:46-65.
44. Lowe RL. Environmental requirements and pollution tolerance of freshwater diatoms. US Environmental Protection Agency, EPA-670/4-74-005. Cincinnati, Ohio, USA; 1974.
45. Descy JP. A new approach to water quality estimation using diatoms. Nova Hedwigia. 1979;64:305-323.
46. Lange-Bertalot H. Pollution tolerance of diatoms as a criterion for water quality estimation. Nova Hedwigia. 1979;64:285-304.
47. Coste M. Study of Biological Me ETHODS Appr'eciation Quantitative Qualit'e of Water. Rapport Q E. Lyon, Agence de l'Eau Rhˆone-M´editerran´ee-Corse-Cemagref, Lyon, France; 1982.
48. Watanabe T, Asai K, Houki A. Numerical estimation to organic pollution of flowing water by using the epilithic diatom assemblage-diatom assemblage index (DAIpo). Sci Total Environ. 1986;55:209-218.
49. Sládeèek V. Diatoms as indicators of organic pollution. Acta Hydroch Et Hydrobiol. 2006;14:555–566.
50. Leclercq L, Maquet B. Two new chemical and diatomic quality indices running water. Application to Samson and sesaffluents. Comparison with other chemical indices biocenotic and diatomic. Inst Roy Sc Natur: Belg, Documents de Travail. 1987;3:113.

51. Steinberg C, Schiefele C. Biological indication of trophy and pollution of running waters. Z Wasser Abwass For. 1987;21:227-234.
52. Schiefele S, Schreiner C. Use of diatoms for monitoring nutrient enrichment, acidification and impact of salt in rivers in Germany and Austria. In: Whitton BA, Rott E, Friedrich G, (eds). Use of algae for monitoring rivers. Düsseldorf, Germany. Institut für Botanik, Universität Innsbruck, Studia Student. G m b H, Innsbruck. 1991;103-110.
53. Rumeau A, Coste M. Introduction to the systematics of freshwater diatoms. For the practical use of a generic diatomic index. B. Fr. Peche Piscic. 1988;309:1-69.
54. Wu JT. A generic index of diatom assemblages as bioindicator of pollution in the Keelung River of Taiwan. Hydrobiol. 1999;397:79-87.
55. Descy JP, Coste M. A test of methods for assessing water quality based on diatoms. Verh int Verein Limnol. 1991;24:2112-2116.
56. Bahls LL. Periphyton bioassessment methods for Montana streams. Montana water quality bureau, department of health and environmental science. Helena, Montana; 1993.
57. Kelly MG, Whitton BA. The Trophic diatom index: a new index for monitoring eutrophication in rivers. J Appl Phycol. 1995;7:433-444.
58. Lenoir A, Coste M. Development of a practical diatom index of overall water quality applicable to the French national water Board network. In Whitton BA, Rott E, (eds). Use of Algae for Monitoring Rivers II, Studia Student G.m.b.H, Innsbruck. 1996;29-43.
59. Prygiel J, Carpentier P, Almeida S, Coste M, Druart JC, Ector L, Guillard D, Honore MA, Iserentant R, Ledeganck P, et al. Determination of the biological diatom index (IBD NF T 90-354): Results of an intercomparison exercise. J Appl Phycol. 2002;14:27-39.
60. Coste M, Boutry S, Rosebery JT, Delmas F. Improvements of the biological diatom index (BDI): Descrip tion and efficiency of the new version (BDI-2006). Ecol. Indicators. 2009;9:621-650.
61. Rott E, Hofmann G, Pall K, Pfister P, Pipp E. Indikationslisten für Aufwuchsalgen. Teil 1. Saprobielle Indikation. Bundesministerium für Land- und Forstwirtschaft. Wien. 1997;1-73.
62. Hill BH. The use of periphyton assemblage data in an index of biotic integrity. Bull N Am Benthol Soc. 1997;14:158.
63. McFarland BH, Hill BH, Willingham WT. Abnormal *Fragilaria* sp. (*Bacillariophyceae*) in streams impacted by mine drainage. J Freshwater Ecol. 1997;12:141-149.
64. Barbour MT, Gerritsen J, SNYDER BD, Stribling JB. Rapid bioassessment protocols for use in streams and wadeable rivers. USEPA, Washington; 1999.
65. Passy SI, Bode RW. Diatom model anity (DMA), a new index for water quality assessment. Hydrobiol. 2004;524:241-251.
66. G´omez N, Licursi M. The Pampean Diatom Index (IDP) for assessment of rivers and streams in Argentina. Aquat Ecol. 2001;35:173-181.
67. Dell'Uomo A. The diatomic index of eutrophication / pollution (EPI-D) in the monitoring of running waters. Guidelines. Agency for Environmental Protection and Technical Services, Rome, Italy; 2004.

68. Griffith MB, Hill BH, McCormick FH, Kaufmann PR, Herlihy AT, Selle AR. Comparative application of indices of biotic integritybased on periphyton, macroinvertebrates, and fishto southern Rocky Mountain streams. Ecol Indicators. 2005;8:117-136.
69. Lavoie I, Campeau S, Grenier M, Dillon PJ. A diatom-based index for the biological assessment of eastern Canadian rivers: an application of correspondence analysis (CA). Can J Fish Aquat Sci. 2006;8:1793-1811.
70. Grenier M, Lavoie I, Rousseau AN, Campeau S. Defining ecological thresholds to determine class boundaries in a bioassessment tool: The case of the Eastern Canadian Diatom Index (IDEC). Ecol Indicators. 2010;10:980-989.
71. Chessman BC, Bate N, Gell PA, Newall P. A diatom species index for bioassessment of Australian rivers. Mar Freshwater Res. 2007;58:542-557.
72. Lavoie I, Vincent WF, Pienitz R. Benthic algae as bioindicators of agricultural pollution in the streams and rivers of southern Québec (Canada). Aquat Ecosyst Health Manage. 2004;7:43-58.
73. Lavoie I, Hamilton PB, Wang YK, Dillon PJ, Campeau S. A comparison of stream bioassessment in Québec (Canada) using six European and North American diatom-based indices. Nova Hedwigia. 2009;135:37-56.
74. Gomez N. Use of epipelic diatoms for evaluation of water quality in the Matanaza-Riachuelo(Argentina), a pampean plain river. Water Res. 1998;32:2029-2034.
75. Hassan GS, Espinosa MA, Isla FI. Modern diatom assemblages in surface sediments from estuarine systems in the southeastern Buenos Aires Province, Argentina. J Paleolimnol. 2006;35:39-53.
76. Hassan S, Espinosa MA, Isla FI. Diatom-based inference model for paleosalinity reconstructions in estuaries along the northeastern coast of Argentina. Palaeogeogr Paleolimnol Palaeoecol. 2009;275:77-91.
77. Lobo EA, Callegaro VLM, Wetzel CE, Hermany G, Bes D. Water quality study of the Condor and Capivara Streams, Porto Alegre Municipal District, RS, Brazil, using epilithic diatom biocenoses as bioindicators. Int J Oceanogr Hydrobiol. 2004;2:77-93.
78. Salomoni SE, Rocha O, Hermany G, Lobo EA. Application of water quality biological indices using diatoms as bioindicators in the Gravatai River, RS, Brazil. Braz J Biol. 2011;71:949-959.
79. Bere T, Tundisi JG. The effects of substrate type on diatom-based multivariate water quality assessment in a trophical river (Monjolinho), São Carlos, SP, Brazil. Water Air Soil Poll. 2011;216:391-409.
80. Bere T, Tundisi JG. Applicability of the Pampean Diatom Index (PDI) to streams around São Carlos-SP, Brazil. Ecol Indicators. 2012;13:342-346.
81. Prygiel J, Coste M. The assessment of water quality in the Artois-Picardie water basin (France) by the use of diatom indices. Hydrobiol. 1993;269:343-349.
82. Rimet F, Cauchie HM, Hoffmann L, Ector L. Response of diatom indices to simulated water quality improvements in a river. J Appl Phycol. 2005;17:119-128.
83. Feio MJ, Almeida SFP, Craveiro SC, Calado AJ. A comparison between biotic indices and predictive models in stream water quality assessment based on benthic diatom communities. Ecol Indicators. 2009;9:497-507.

84. Berthon V, Bouchez A, Rimet F. Using diatom life-forms and ecological guilds to assess organic pollution and trophic level in rivers: a case study of rivers in south-eastern France. Hydrobiol. 2011;673:259-271.

85. Rott E, Pipp E, Pfister P. Diatom methods developed for river quality assessment in Austria and across-check against numerical trophic indication methods used in Europe. Algol Studies. 2003;110:91-115.

86. Hering D, Johnson R, Kramm S, Schmutz S, Szoszkiewicz K, Verdonschot PFM. Assessment of European streams with diatoms, macrophytes, macroinvertebrates and fish: a comparative metric-based analysis of organism response to stress. Freshwater Biol. 2006;51:1757-1785.

87. Tison J, Giraudel JL, Coste M. Evaluating the ecological status of rivers using an index of ecological distance: An application to diatom communities. Ecol Indicators. 2008;8:285-291.

88. Besse-Lototskaya A, Verdonschot PFM, Coste M, Van De Vijver B. Evaluation of European diatom trophic indices. Ecol Indicators. 2011;11:456-467.

89. Delgado C, Pardo I, García L. Diatom communities as indicators of ecological status in Mediterranean temporary streams (Balearic Islands, Spain). Ecol Indicators. 2012;15:131-139.

90. Archibald REM. Diversity in some South African diatom associations and its relation to water quality. Water Res. 1992;6:1229-1238.

91. Schoeman FR. Diatom indicator groups in the assessment of water quality in the Jukskei-Crocodile river system (Transvaal), republic of South Africa. J Limnol Soc South Afr. 1976;2:21-24.

92. Schoeman FR. Diatoms as indicators of water quality in the upper Hennops River (Transvaal, South Africa). J Limnol Soc South Afr. 1979;5:73-78.

93. Taylor JC, Janse Van Vuuren MS, Pieterse AJH. The application and testing of diatom-based indices in the Vaal and Wilge Rivers, South Africa. Water S A. 2007;33:51-59.

94. Beyene A, Addis T, Kifle D, Legesse W, Kloos H, Triest L. Comparative study of diatoms and macroinvertebrates as indicators of severe water pollution: Case study of the Kebena and Akaki rivers in Addis Ababa, Ethiopia. Ecol Indicators. 2009;9:381-392.

95. Chaïb N, Tison-Rosebery J. Water quality assessment and application of the biological diatom index in the Kebir-East wadi, Algeria. Afr J Aquat Sci. 2012;37:59-69.

96. Wu JT. Relation of change in river diatom assemblages to water pollution. Bot Bull Acad Sinica. 1986;27:237-245.

97. Lobo EA, Katoh K, Aruga Y. Response of epilithic diatom assemblages to water pollution in rivers in the Tokyo Metropolitan area, Japan. Freshwater Biol. 1995;34:191-204.

98. Jüttner I, Sharma JS, Dahal BM, Dahal BM, Ormerod SJ, Chimonides PJ, Cox EJ. Diatoms as indicators of stream quality in the Kathmandu valley and middle hills of Nepal and India. Freshwater Biol. 2003;48:2065-2084.

99. Duong TT, Coste M, Feurtet-Mazel A, Dang DK, Gold C, Park YS, Boudou A. Impact of urban pollution from the Hanoi area on benthic diatom communities collected from the Red, Nhue and Tolich rivers (Vietnam). Hydrobiol. 2006;563:201-216.

100. Atazadeh I, Sharifi M, Kelly MG. Evaluation of the trophic diatom index for assessing water quality in River Gharasou, western Iran. Hydrobiol. 2007;589:165-173.
101. Wu NC, Cai QH, Fohrer N. Development and evaluation of a diatom-based index of biotic integrity (D-IBI) for rivers impacted by run-of-river dams. Ecol Indicators. 2012;18:108-117.
102. Siva CJ, John J. Urban land use and periphytic diatom communities: a comparative study of three metropolitan streams in Perth, Western Australia. Proceedings of the 15th international diatom symposium, Perth, Australia. 1998;125-134.
103. John J. Assessment of river health in Australia by diatom assemblages-a review. Int J Oceanogr Hydrobiol. 2004;33:95-104.
104. Haese RR, Murray EJ, Smith MCS, Smith J. Diatoms control nutrient cycles in a temperate, wave-dominated estuary (Southeast Australia). Limnol Oceanogr. 2007;52:2686-2700.
105. Flotemersch JE, Stribling JB, Paul MJ. Concepts and approaches for the bioassessment of non-wadeable streams and rivers. USEPA, Washington; 2006.
106. Kerans BL, Karr JR. A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee valley. Ecol Appl. 1994;4:768-785.
107. Weigel BM, Henne LJ, Martinez-Rivera LM. Macroinvertebrate-based index of biotic integrity for protection of streams in west-central Mexico. J N Am Benthol Soc. 2002;21:686-700.
108. Blocksom KA, Kuptenbach JP, Klemm DJ, Fulk FA, Cormier SM. Development and evaluation of the lake macroinvertebrate integrity index (LMII) for new Jersey lakes and reservoirs. Environ Monit Assess. 2002;77:311-333.
109. Hughes RM. Defining acceptable biological status by comparing with reference conditions. Pages 31-47 in Davis W, Simon T, eds. Biological assessment and criteria: tools for water resource planning and decision making. Lewis, Chelsea, MI; 1995.
110. Hughes RM, Peck DV. Acquiring data for large aquatic resource surveys: the art of compromise among science, logistics and reality. J N Am Benthol Soc. 2008;27:837-859.
111. Bonar S, Hubert W, Willis D, (eds.). Standard methods for sampling North American freshwater fishes. American Fisheries Society. Bethesda, Maryland; 2009.

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