

Role of environmental variables in diatom distribution in urban wetlands of Peninsular India

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Abstract

Unplanned anthropogenic activities have contributed to the shrinkage of wetlands as well as degrading their quality. This necessitates watershed-based planning such as inventorying, mapping and regular monitoring with cost-effective and reliable assessment protocols. Diatoms have been used across continents as bioindicators for reflecting the physical, chemical and biological integrity of their habitats. The current study attempts to understand the role of environmental factors in the formation of the diatom community structure in the shallow wetlands of Peninsular India. Diatoms from different habitats and water chemical variables were assessed for 43 wetlands of Bangalore, a profoundly urbanized region of Peninsular India. A total of 181 diatom taxa from 45 genera highlights the rich biodiversity of the region. Wetlands located in the densely populated urban regions are dominated by a prolific growth of eutrophic indicator species such as *Gomphonema parvulum* Kütz., *Nitzschia palea* (Kütz.) W.Sm., *N. umbonata* (Ehrenb.) Lange-Bert., *Diadismis confervacea* Kütz., *Cyclotella meneghiniana* Kütz. and *C. atomus* Hust. Wetlands located at the outskirts of the city characterize oligo-mesotrophic conditions where *Achnantheidium* sp. dominates. Detrended canonical correspondence analysis showed a strong influence of eutrophication and organic/inorganic pollution on diatom assemblages but a relatively weak influence of conductivity. TWINSpan shows grouping of wetlands based on species composition and suggests that *Achnantheidium* sp. and *Cyclotella meneghiniana* are initial indicator taxa for oligo-mesotrophic and eutrophic conditions respectively. These results indicate that the environmental factors consistently act as limiting variables in structuring diatom assemblages at a regional scale in urban ecosystems. The study provided insights into the ecological importance of endemic diatoms found in different environments. Thus, diatom-based biomonitoring can become a viable surrogate for physical and chemical parameters of water quality. Also, region-specific diatom indices will enable the easy and efficient investigations of wetlands.

Key index words: algae, diatoms, Bangalore, habitat specificity, Peninsular India, water management

Introduction

Biota, particularly algae (chlorophyta, cyanophyta, bacillariophyta and other algae) of lentic and lotic ecosystems, respond to the environmental changes due to the sustained inflow of pollutants. Among algae, diatoms respond quickly to any subtle changes in the environmental conditions (due to the inflow of pollutants or habitat alterations) and hence they are the most promising tool in biomonitoring (Kelly *et al.* 1998, Pouličková *et al.* 2004, Solak & Ács 2011). The relationship between diatoms and environmental variables had been studied earlier in Europe, North America, South Africa and East Asia, but such studies expand to diverse corners of the world in this century (van Dam *et al.* 1994, Blanco *et al.* 2007, Karthick *et al.*, 2011). Understanding cosmopolitan-endemism and the relative preference for

pristine or polluted waters form the base for developing diatom based indices for implementing regular diatom based monitoring. Community structure of diatoms are specific to each eco-region and significantly varies from pristine to polluted water bodies and this helps in distinguishing oligotrophic from eutrophic water bodies. For example, *Gomphonema stoermeri* Kociolek & Kingston, probably endemic to western North America, dominates pristine water bodies in the area (Kociolek & Kingston 1999). In India, *Achnantheidium chitrakootense* Wojtal *et al.* is common in Himalayan streams which are electrolyte-rich and contain high amounts of dissolved oxygen (Wojtal *et al.* 2010), while polluted waters in urban wetland are often dominated with *Nitzschia taylorii* Alakananda *et al.* (Alakananda *et al.* 2011, 2012).

Urban water bodies exhibit high spatio-temporal variations in temperate and tropical regions that influence the distribution pattern and biodiversity of diatoms. The diatom to environment relationship is studied intensely in temperate regions (Cejudo-Figueiras *et al.* 2010) and

it might not be homogenous (with similar species composition) in other continents like Asia (Goulden 2011). It will be hence an important goal for limnologists and environmental policy makers to understand the eco-region specific diatom distribution and delimit the main limnological variables influencing the species pattern. The influence of physical and chemical variables on diatom distribution in different environmental types needs to be investigated for subsequently developing region specific diatom indices.

Urban wetlands of peninsular India are vital ecosystems, providing services such as water for domestic use, and moderating atmospheric temperature while balancing biodiversity (Ramachandra & Kumar 2008). Previous studies have focused mainly on physical and chemical factors for urban water management, thus excluding other factors such as land-use type in watershed region, and biological organisms and its response to environmental shifts. Humane *et al.* (2010) and Sharma *et al.* (2011) focused on the diatom distribution and sediment analysis from various environments in India. Precise ecological aspects, ionic and nutrient related species variations are yet to be explored in classifying water quality classes for prioritizing more polluted wetlands and identifying indicator species for further environmental management in urban wetlands like that of Bangalore region. Since 1960s, Bangalore has rapidly changed from a lake city to urbanized city with indiscriminate disposal of solid and liquid wastes and unplanned developmental activities. This has amplified pollution levels, which is evident from excess nutrients and organic components affecting the trophic levels thereby declining biodiversity and ecosystem activities. Diatom based monitoring as a surrogate for the conventional water quality parameters is not being practiced in India, especially in wetland systems. Thus, the study of diatom composition and exploring diatom-environment relationship through monitoring is a novel cost-effective approach and has scope for the replication and application at a regional scale in wetland management plans. In this context, the study aims to investigate the diatom community composition along rural-urban gradient reflecting significant environmental variables and classify wetlands based on the key indicator taxa that reflect ecological status of wetlands.

Study area

Bangalore with a current population of 9.5 million is located at 12°39' to 13°18'N and 77°22' to 77°52'E at an average elevation of 900 m above sea level (Fig. 1). It represents a semi-arid to arid region with soil type varying from red loamy to laterite and physiography ranges from rocky upland, plateau to flat-topped hills that form a

slope at south and south east along with Pediplains along western parts (<http://cgwb.gov.in>). Bangalore's topography had allowed the creation of a large number of inter-connected water bodies during the 16th century at the time of Kempe Gowda and the Wodeyar dynasty making provision for the traditional uses of irrigation, drinking, fishing and washing. Four valleys, viz. Hebbal, Koramangala, Challaghatta and Vrishabhavathi, of the Bangalore metropolitan region drained the rainwaters through interconnected wetlands. Recent studies reveal that there has been a 63.2% increase in built-up area with 78% loss of vegetation cover and 79% loss of wetlands in Bangalore (Ramachandra & Kumar 2008). Studies based on spatial metrics indicate the radial pattern of urbanisation in Bangalore i.e., urban patches are clumped at city center but are more fragmented towards the periphery with very few clustered urban patches (Ramachandra *et al.* 2012). In the past 10 years, numerous wetlands at urban pockets were degraded due to the sustained inflow of untreated or partially treated waste water from densely populated, domestic and industrial localities. However, wetlands situated at city margin/peripheral regions in less populated are exposed to less anthropogenic activities (Sudhira *et al.* 2007) and maintain pristine status.

Methods

Diatom and water sampling

Diatom samples were collected from a total of 106 sampling sites of 43 wetlands of Bangalore watershed region during February–April 2009 and February–April 2010 following guidelines as per standard protocols (Karthick *et al.* 2010). Post monsoon period was chosen to avoid the diluted water quality and the studied wetlands and sampling codes are listed in Annexure 1. The wetlands and sampling sites were prioritized based on the earlier studies carried out by Bengaluru Bruhat Mahanagara Palike (BBMP). Thirty wetlands are situated in the densely built-up areas (residential and industrial areas) characterized by waste inflow and less water inflow. The remaining thirteen wetlands were situated in less populated regions at the city's periphery.

Diatom sampling was carried out covering all possible habitats viz., plants (epiphytic diatoms), stones (epilithic diatoms) and sediments (epipelc diatoms). Samples were cleaned following hot HNO₃ and HCl method. Slides of cleaned samples were prepared using Naphrax (refractive index, r.i. 1.74) as mounting agent and 400 frustules were counted under the Olympus light microscope BX-51 with DIC at 1000×. Taxa were identified up to the species level (and not up to variety level) in order to avoid 'force fit' identification of tropical taxa to European and North American taxa. Identification was performed by referring the standard key literatures

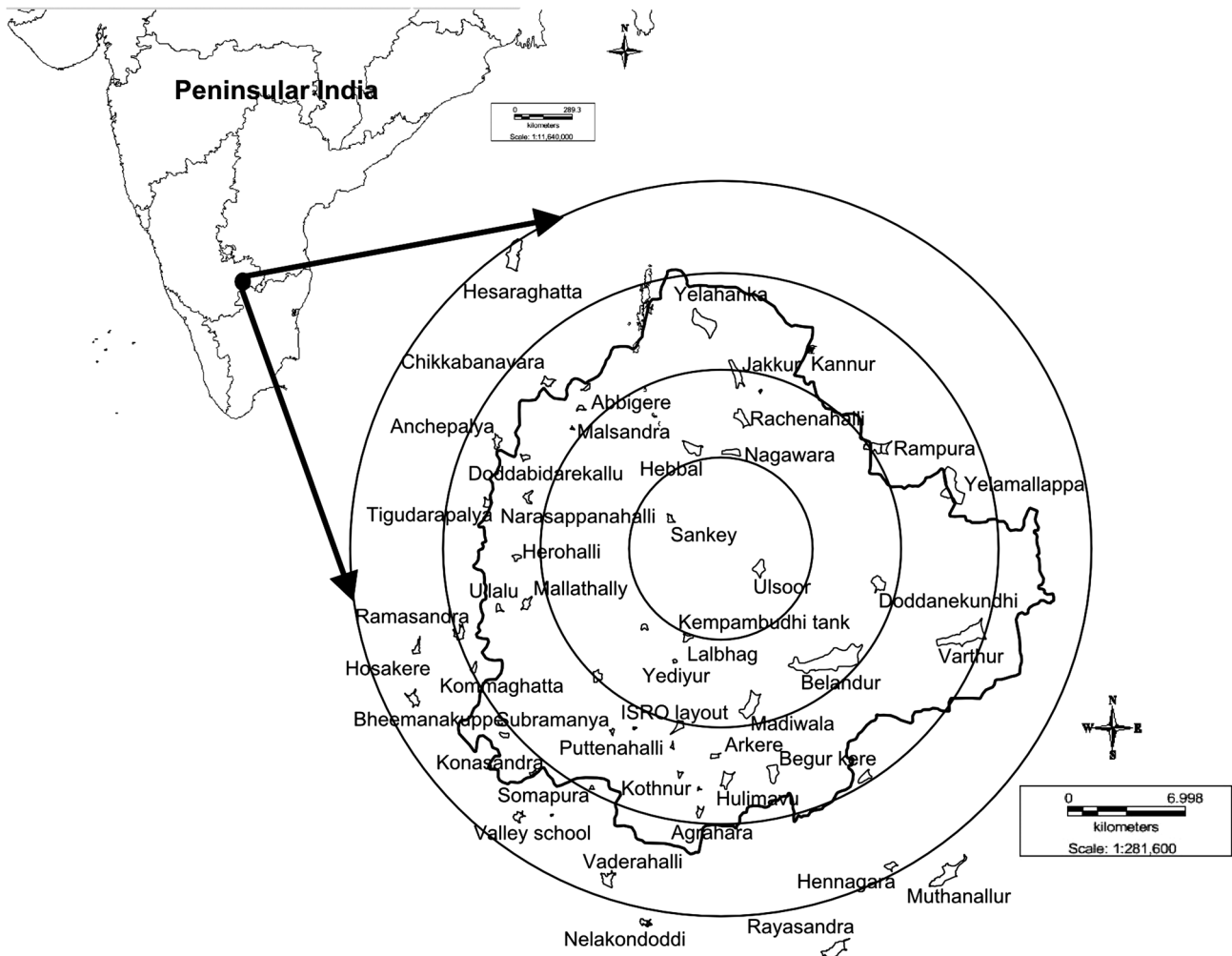


Fig. 1. Distribution of 43 sampled wetlands in Bangalore.

(Krammer & Lange-Bertalot 1991, Lange-Bertalot 2001, Taylor *et al.* 2007b). Water samples were collected along with diatom samples for analyzing environmental variables from various points. Water temperature (WT), dissolved oxygen (DO), total dissolved solids (TDS), salinity (SAL), pH and electric conductivity (EC) were measured on site using EC500 pH conductivity meter (Extech, Massachusetts). Nutrient concentrations, namely, nitrates (N) and phosphates (P), major ions chlorides (CL), total hardness (TH), calcium hardness (CaH), magnesium hardness (MgH), alkalinity (ALK), chemical oxygen demand (COD) and biological oxygen demand (BOD) were analyzed in the laboratory by following APHA (2005).

Data analysis

Diatom taxa occurring in at least one sample with a relative abundance >10% were considered for further statistical analyses to understand inter and intra distributional pattern and its relationship with water conditions. Detrended canonical correspondence anal-

ysis (DCCA), a direct multivariate gradient analysis, was performed using CANOCO for windows 4.5 (ter Braak 1986) to evaluate the relationship between environmental variables and diatom species composition patterns (or distribution). DCCA attempts to remove arch effect in samples and spreads the points to avoid a clumping pattern. Two-way indicator species analysis (TWINSPAN) was performed through TWINSPAN for Windows (WinTWINSPAN) version 2.3 developed by Hill & Šmilauer (2005). This software considers the classification of samples first and then the classification of species based on its ecological preferences. TWINSPAN classifies the sampling points according to the relative abundance of species and defines diatom community types based on the reciprocal averaging (Gauch 1982). It performs well in the classification of benthic assemblages when compared with other clustering techniques.

Results

Diatom distribution

A total of 181 diatom taxa belonging to 45 genera were identified from 43 wetlands (refer annexure 2). *Achnantheidium* sp., *Gomphonema* sp. and *Nitzschia* sp. were considered for a detailed taxonomical investigation using scanning electron microscopy (SEM) due to the complexity of these species and its characteristics. Among all, only 6% of total taxa showed a relative abundance (RA) of >50%, hence species with >10% RA present in at least 1 sampling site was considered for further analysis. Distribution of diatoms with species composition has been given in Figure 2a & b. Figure

2a comprised sampling sites with occurrence of >10% RA of *Cyclotella meneghiniana* Kütz., *Nitzschia palea* (Kütz.) W.Sm., *Seminavis strigosa* (Hust.) Danielidis et Econ.-Amilli and *Gomphonema parvulum* Kütz. or either one of these species. Wetlands in Figure 2b predominantly contained *Achnantheidium* sp. in almost all sites, while, *Fragilaria ulna* var. *acus* (Kütz.) Lange-Bert., being abundant at Ulsoor wetland, reflected a conductivity rich condition. Other taxa unique to a specific wetland were *Gomphonema gracile* Ehrenb. at Hesaraghatta (HG), *Navicula symmetrica* Patrick at Chickbanavara (CK), *Gomphonema dharvarensis* H.P. Gandhi at Somapura (SM), *Nitzschia taylorii* Alakananda et al. and *Gomphonema spiculoides* H.P. Gandhi at Begur (BG).

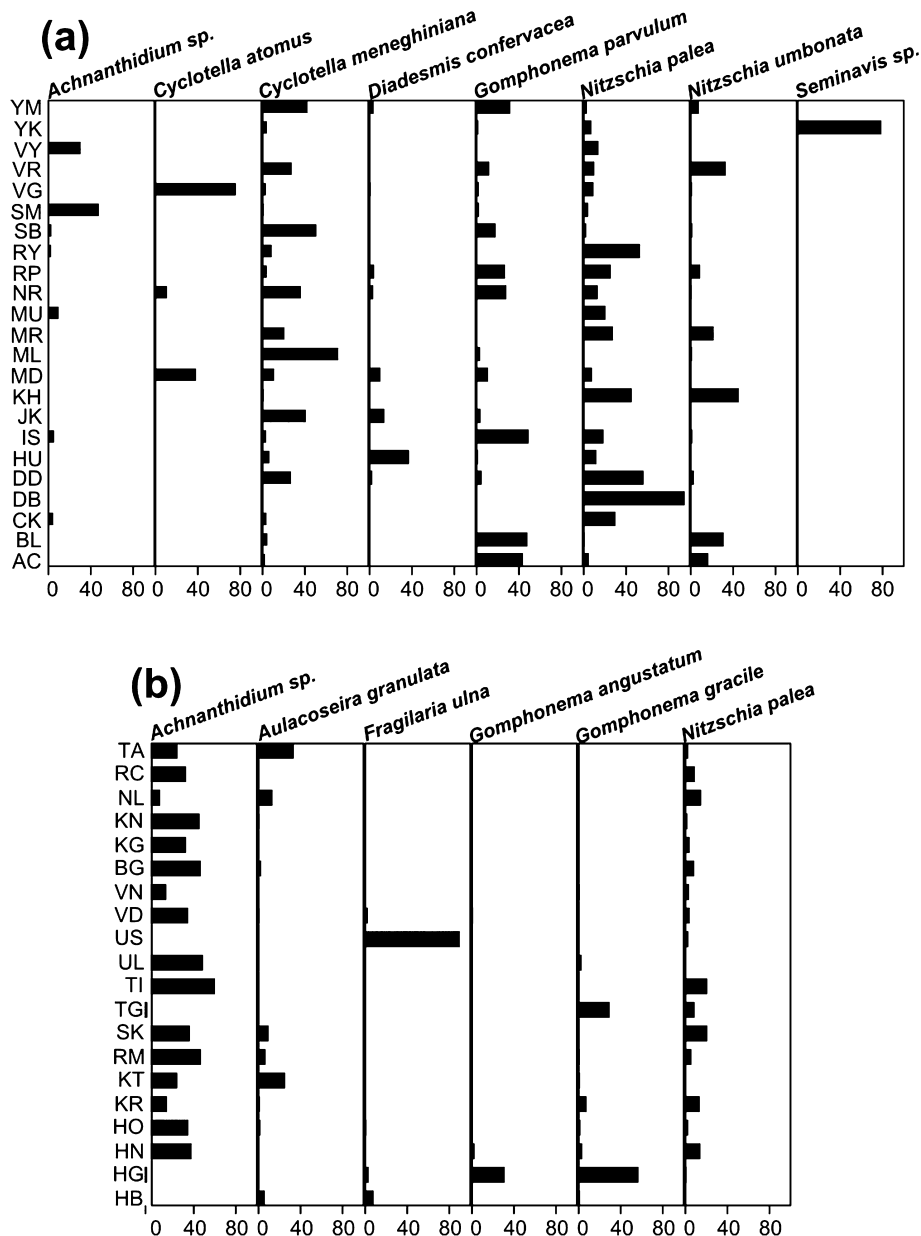


Fig. 2. Diatom composition and relative abundance of the dominant and common diatom species across 43 wetlands. Refer annexure 2 for all recorded taxa.

Water quality analysis

Table 1 reveals that there is a considerable variation in the water chemical characteristics in the wetlands of Bangalore region. Increasing levels of conductivity, biological oxygen demand and chemical oxygen demand were recorded in wetlands of urban pockets. High levels of electric conductivity (range, 46–11,025 $\mu\text{S cm}^{-1}$) was recorded at Varthur, Rampura, Anchepalya, Dodanekundi, Yellamallappa chetty and Yelahanka wetlands which were characterized as highly populated and industrially developed regions, where pollution levels exceeded the Bureau of Indian Standards [BIS] of surface waters. Dissolved oxygen levels have been recorded as 0 or $<0 \text{ mg L}^{-1}$ at sewage fed wetlands located at northwest and southeast parts of Bangalore region, which also comprised of high-mineralized inflow. Untreated sewage was found to be the main source of pollution at densely populated sites while lower conductivity and high oxygen levels (10.7 mg L^{-1}) were recorded in wetlands located in rural/peripheral region. Due to the degradation and low oxygen levels, these wetlands showed increased levels of biological oxygen demand (range, 2.2–73.09 mg L^{-1}) and chemical oxygen demand (range, 10.7–240 mg L^{-1}). The superfluous amount of chlorides (range, 28–859 mg L^{-1}) in water indicates the accumulation of salt from road construction and domestic waste inflow. During the present study, the hardness varied from 64 to 766 mg L^{-1} , phosphate varied from 0.02 to 2.74 mg L^{-1} and nitrate varied from 0.01 to 2.11 mg L^{-1} .

Detrended Canonical Correspondence analysis (DCCA)

Detrended Canonical correspondence analysis (DCCA) provided the ordination of species in relation with chemical variables (Table 2, Fig. 3). The spe-

cies-environmental correlations in DCCA axis 1 (0.827) and axis 2 (0.705) were significant ($p < 0.01$) explaining 29.5% and 17.4% of the species environmental relation with eigenvalues of 0.489 and 0.288 respectively. The axis 1 mainly showed eutrophication level, but also correlated with parameters related to organic/inorganic pollution. *Staurisira pinnata* and *Fragilaria ulna* var. *acus* had a larger score, while species such as *Gomphonema spiculoides* and *Gyrosigma rautenbachiae* had a relatively small score. The axis 2 was mainly explained by pH. *Amphora veneta* and *G. rautenbachiae* had a larger score (i.e. negatively correlated with pH), while *Gomphonema angustum* had a relatively small score (i.e. positively correlated with pH).

TWINSPAN

Classification analysis using TWINSPAN (Fig. 4) resulted in 7 groups from 106 samples. The first TWINSPAN division separated oligo-mesotrophic electrolyte-poor wetlands from eutrophic, electrolyte-rich wetlands. A further division (on the left side) aided in distinguishing oligotrophic wetland Hesaraghatta (HG) from the rest of the sites, which are under mesotrophic/moderate pollution (as in DCCA). This group was indicated by *Achnantheidium* sp. The division towards right half covered 2 groups i.e., eutrophic wetlands indicated by *Cyclotella atomus* Hust. and *F. ulna* var. *acus* and, hypertrophic group dominated with *N. palea*. The other indicator taxa recognized were *N. umbonata*, *C. meneghiniana* and *G. parvulum*. Indicator species *Gomphonema gracile* Ehrenb., *G. dharwarensis* and *Achnantheidium* sp. were differential species for groups A to C while *G. parvulum*, *C. meneghiniana* and *N. umbonata* were differential for groups D and E. Groups F and G were dominant and characteristic with *N. palea*. Group A to C sites covered wetlands that were classified into oligo-mesotrophic (DCCA) and sampling sites under D–E comprising of

Table 1. Details of average and range (maximum (Max) & minimum (Min)) of selected water quality variables from Bangalore region's wetlands.

Water quality variables (Units)	Min	Max	Average
pH	7.0	10.0	8.6
Water Temperature, WT ($^{\circ}\text{C}$)	20.8	35.0	29.5
Electric conductivity, EC ($\mu\text{S cm}^{-1}$)	46	11025	1387
Total Dissolved Solids, TDS (mg L^{-1})	28	7660	1002
Salinity, SAL (mg L^{-1})	17	5415	687
Dissolved oxygen, DO (mg L^{-1})	0.0	10.73	6.3
Biological oxygen demand, BOD (mg L^{-1})	2.2	73.0	22.3
Chemical oxygen demand, COD (mg L^{-1})	10.7	240.0	59.2
Nitrates, N (mg L^{-1})	0.01	2.11	0.34
Phosphates, P (mg L^{-1})	0.01	2.74	0.57
Total Hardness, TH (mg L^{-1})	64	766	257
Chlorides, CL (mg L^{-1})	28	859	226
Total Alkalinity, ALK (mg L^{-1})	92	1080	377

Table 2. Summary of the Detrended canonical correspondence analysis (DCCA) for 43 wetlands.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.489	0.288	0.177	0.094	8.001
Species-environment correlations	0.827	0.705	0.606	0.437	
Cumulative percentage variance					
species data:	6.1	9.7	11.9	13.1	
species-environment relation:	29.5	46.9	57.5	63.2	

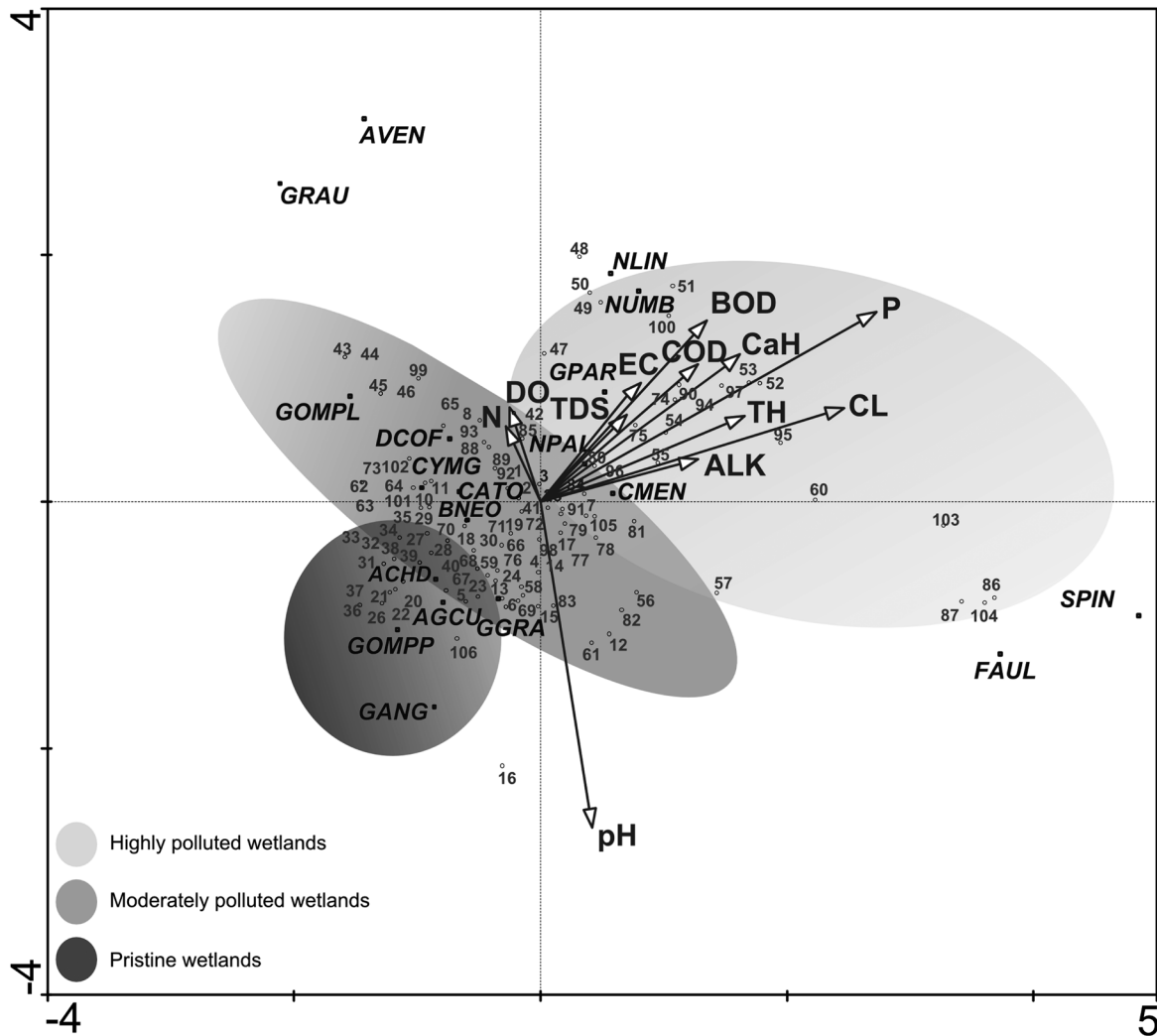


Fig. 3. DCCA ordination diagrams of diatom communities' samples from 106 sampling sites. The arrow and labels in block letters indicates the environmental variables, numbers refers to sampling sites (refer annexure 1) and labels in italics refers to species name (Refer annexure 2).

eutrophic status wetlands that were clustered as meso to eutrophic in Figure 3. However, TWINSPAN groups F and G comprised of severely polluted wetlands that are hypereutrophic sites dominated by mixotrophic species *N. palea*.

Discussion

The data analysis of 106 samples collected from urban water bodies highlights the role of environmental drivers

in structuring diatom species assemblages, conforming to the earlier studies (Taylor *et al.* 2007a). Elevated ionic level is proportional to the dissolved major elements (cations and anions like calcium, chlorides, sodium and magnesium) that have influenced the aquatic biota, sedimentation process and oxygen levels which adversely affected the availability of microhabitats (Leira & Cantonati 2008). Ions accumulate with the sustained inflow of sewage and industrial effluents (human activities) or originate from mineral sources such as erosion of

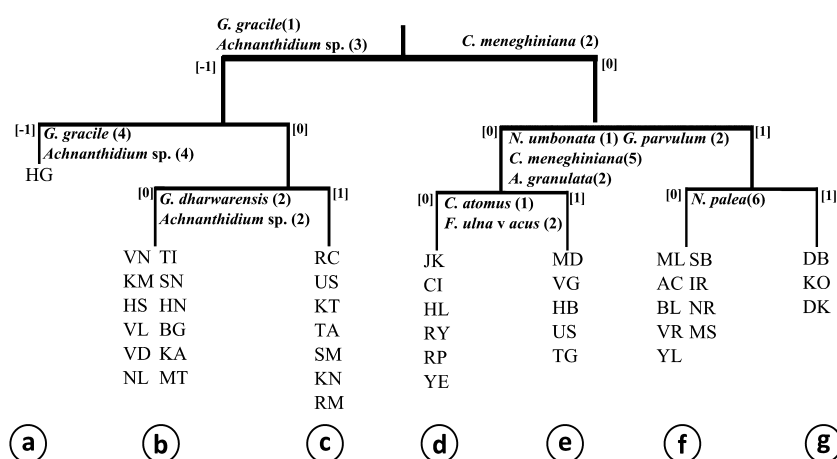


Fig. 4. Indicator species of the main divisions from TWINSpan classification for 43 samples. The numbers following the species name indicate the categories of relative abundance (1: 0–2%; 2: 2–5%; 3: 5–10%; 4: 10–20%; 5: 20–40%). Refer annexure 1 for wetland codes.

rocks and soils (natural activities). The increased sedimentation rates imbalances the biological and chemical oxygen demand in water and thus becomes responsible for species shift. These are the characteristics of polluted water bodies which resemble the wetlands of the current study region (Table 1). In the current study, wetlands in urban/populated pockets showed higher nutrient and ionic load, which is evident in DCCA. Natural organic detritus/organic waste from wastewater, agriculture and urban runoff attributed to higher BOD and COD. It also explained diminishing DO levels that are lethal for most fishes, many aquatic insects and amphibians (Kar *et al.* 2006). High chloride was due to point source (sewage inputs), road deicing salts and weathering (Müller & Gächter 2012) and are directly related to urbanization and increasing human density (Brönmark & Hansson 2005).

Diatom composition and distributional pattern across wetlands were comparable to environmental variables. Species composition comprised of cosmopolitan and endemic species of the genus *Gomphonema*, *Nitzschia* and *Surirella* (Fig. 2). Among 43 wetlands, 10 wetlands recorded the presence of endemic diatoms with relative abundance ranging from 5 to 65% across habitats. Most dominant endemic diatoms include *G. dharwarensis*, *G. spiculoides*, *Surirella* sp., *Nitzschia williamsii* Alakananda *et al.* and *N. taylorii*. A recent study (Karthick & Kociolek 2012, Karthick *et al.* 2012) reported high abundance of many endemic diatoms such as *Gomphonema gandhii* Karthick *et al.*, *Gomphonema diformum*, *Gomphonema tamilensis* Karthick & Kociolek from this region. Further, these studies emphasized the need for understanding the ecological profile of endemic species and its role in biomonitoring programs in the Indian subcontinent. For example, *G. dharwarensis* grows abundantly in low nutrient and highly aerated waters and hence forms a potential indicator species of oligotrophic condition.

Further, many unidentified species of *Achnanthydium* and *Gomphonema* which occurred in this study are in the process of taxonomic description along with the study of their ecological preference which will be helpful for future biomonitoring work in this part of the continent. Most of the new diatoms occurring in low to moderately polluted waters from this region have higher ecological importance, and also play a vital role in classifying wetlands either based on already available indices or in formulating a new index for peninsular India. This ensures the importance of endemic diatoms in tropical urban waters in bioassessment programs and eventually helps in the conservation of these highly threatened fragile wetlands of peninsular India.

Species such as *Rophalodia gibba*, *Surirella* sp. and *Cymbella* sp. are substrate specific and grow abundantly on sediment (epipelic) and plant (epiphytic) substrates. Among all others, 90% of species showed no substrate specificity because of less competition for growth of pollution tolerant species in high electrolyte waters (Liancourt *et al.* 2005). This could be attributed to the abundant availability of submerged macrophytes in most of the wetlands unlike in multi-substrate environments (rivers and streams). Recent studies in India recorded diatoms from epiphytic and epilithic habitats of rivers and streams, explaining substrate specific diatom assemblages (Humane *et al.* 2010, Karthick *et al.* 2011). Based on the availability pattern, recent standard protocol suggested the use of epilithic diatoms for monitoring of lotic ecosystems such as rivers and streams (Kelly *et al.* 1998, Karthick *et al.* 2010) and epiphytic diatoms for monitoring lentic ecosystems such as wetlands (Stenger-Kovács *et al.* 2007, Cejudo-Figueiras *et al.* 2010). Although epipelic diatoms are used in most studies, it is implemented in exploring paleo-limnological characters i.e., past water quality of lakes (Wang *et al.* 2012). Collection of all available substrates is recommended for better

understanding of species-environment relationships (Winter & Duthie 2000, Alakananda *et al.* 2011). Again, there is a lack in understanding of complex autecology (physical substrate and chemical habitat). The relationship between increasing pollution and substrate type would substantiate the need for further investigation of species autecology in urban region.

DCCA was performed to analyze the relationship of diatom community to water chemistry and results showed a gradient of conductivity and organic load from rural wetlands to urban wetlands and to sewage fed wetlands (Fig. 3). Subsequently, a gradual shift from sensitive species (left side of the plot) to pollution tolerant species (right side of the plot) highlights dissimilar diatom composition in rural, suburban and urban wetlands. The increasing populations in urban pockets showed a proportional increase in degradation of surrounding wetlands due to a high amount of untreated domestic sewage ending up in wetlands. The rapid unplanned urbanisation (Ramachandra *et al.* 2012) and its impact on water bodies was evident from DCCA through diatom composition. However, Sankey, Venkateshpura and Ullalu wetlands are relatively oligotrophic despite being located in urban pockets due to the recent endeavor by the government in restoring these lakes and letting only treated water into these water bodies. DCCA tri-plot demonstrates that organic matter and phosphates are determining factors for assessing the absence of sensitive species and prolific growth of tolerant species in polluted waters and hence they have been aptly used as surrogate indicators of urban development in the earlier studies (Walker & Pan 2006, Walsh & Wepener 2009). TWINSPAN (Fig. 4), shows oligotrophic status with the presence of *Achnantheidium* sp., *Gomphonema* sp. and *G. gracile* (group A–C); mesotrophic status with *C. atomus* and *Fragilaria ulna* (group D & E); and meso-eutrophic status by *N. palea* and *C. meneghiniana* (group F & G). TWINSPAN in Walker and Pan (2006) demonstrated that the diatom composition consistently differ between urban and rural sites, particularly in terms of conductivity and organic pollution. DCCA in other studies from Europe, North America and South America explained the correlation of ions such as potassium, chlorides and calcium with changes in species assemblage (De Fabricius *et al.* 2003, Jüttner *et al.* 2010), due to the intense anthropogenic activities. Factors such as canopy cover, water velocity, light penetration and organic matter affect sensitive diatoms in rivers but in slow flowing/stagnant environments like wetlands, ion concentrations influence diatom assemblages, mainly of tolerant species. Abundant population of *N. palea* is observed in high nitrates and silt conditions, similar to the earlier scores (Van Dam *et al.* 1994) in European waters. Along with *N. palea*, other species of *Nitzschia* inhabit a majority of

wetlands and ecological profiling of these may be very helpful in future for wetland monitoring. These pollution tolerant groups of species also reflect an intense land use change in the catchment such as the conversion of an area under vegetation into an urban pocket (Bere & Tundusi 2011). Wetlands of ecological importance are ranked from most polluted to least polluted based on marked factors (phosphorus, BOD and COD) in DCCA.

Acknowledgement

We thank the Ministry of Science and Technology (DST), Government of India and Indian Institute of Science for financial assistance and infrastructure support. We are grateful to Gururaja, K.V., Jonathan, C., Taylor, J.C. and Karthick, B. for suggestions on statistical analysis and on earlier versions of the manuscript. We thank anonymous reviewers for very useful comments and suggestions, which significantly improved the manuscript. We thank Mr. Susanto Sen for language editing of the final version of the manuscript.

References

- Alakananda, B., Mahesh, M.K., Karthick, B. & Ramachandra, T.V. 2011. Diatom based pollution monitoring in urban wetlands. *The IUP Journal of Soil and water Sciences* **4**(2): 1–22.
- Alakananda, B., Mahesh, M.K., Hamilton, P.B., Supriya, G., Karthick, B. & Ramachandra, T.V. 2012. Two new *Nitzschia* species from shallow wetlands of Peninsular India. *Phytotaxa* **54**:13–25.
- APHA. 2005. Standard methods for the examination of water wastewater, 21st Edition, American Public Health Association, Washington DC, 1368 pp.
- Bere, T. & Tundisi, J.G. 2011. Diatom based water quality assessment in streams influenced by urban pollution: Effects of natural and the selected artificial substrates. *Brazilian Journal of Aquatic Science and Technology* **15**(1): 54–63.
- Blanco, S., Romo, S., Fernández-Aláez, M. & Bécares, E. 2007. Response of epiphytic algae to nutrient loading and fish density in a shallow lake: a mesocosm experiment. *Hydrobiologia* **600**: 65–76.
- Brönmark, C. & Hansson, L.A. 2005. The biology of lakes and ponds. 285 pp. Oxford University Press, Oxford.
- Cantonati, M., Corradini, G., Jüttner, I. & Cox, E.J. 2001. Diatom assemblages in high mountain streams of the Alps and the Himalaya. *Nova Hedwigia* **123**: 37–61.
- Cejudo-Figueiras, C., Blanco, S., Álvarez-Blanco, I., Ector, L. & Bécares, E. 2010. Nutrient monitoring in Spanish wetlands using epiphytic diatoms. *Vie et Milieu* **60**: 89–94.
- De Fabricius, A.L., Maidana, N., Gómez, N. & Sabater, S. 2003. Distribution patterns of benthic diatoms in a Pampean river exposed to seasonal floods: the Cuarto River (Argentina). *Biodiversity & Conservation* **12**: 2443–2454.
- Gauch, H.G. 1982. Multivariate analysis in community ecology. 298 pp. Cambridge university press, Cambridge.
- Goulden, C.E. 2011. The need for capacity building for biomonitoring of lakes and streams in Asia. *Lakes & Reservoirs: Research and Management* **16**: 159–163.

- Hill, M.O. & Šmilauer, P. 2005. TWINSpan for Windows version 2.3. 29 pp. Centre for Ecology and Hydrology & University of South Bohemia, Huntington & Ceske Budejovice.
- Humane, S.K., Bokade, P.R., Humane, S.S. & Wankhade, A.S. 2010. Trophic status ecological studies of the Ambazari Lake, Nagpur, Maharashtra, based on sedimentary diatoms. *Current Science* **99**: 816–822.
- Jüttner I., James, P.C. & Ormerod, S.J. (2010). Using diatoms as quality indicators for a newly formed urban lake and its catchment. *Environmental Monitoring and Assessment* **162**: 47–65.
- Kar, D., Nagarathana, A.V., Ramachandra, T.V. & Dey, S.C. 2006. Fish diversity and conservation aspects in an aquatic ecosystem in northeastern India. *Zoos Print Journal* **21**: 2308–2315.
- Karthick, B. & Kociolek, J.P. 2012. Reconsideration of the *Gomphonema* (Bacillariophyceae) species from Kolhapur, Northern Western Ghats, India: Taxonomy, typification and biogeography of the species reported by H.P. Gandhi. *Phycological Research* **60**: 179–198.
- Karthick, B., Hamilton, P.B. & Kociolek, J.P. 2012. Taxonomy and biogeography of some *Surirella* Turpin (Bacillariophyceae) taxa from Peninsular India. *Beihefte zur Nova Hedwigia* **141**: 81–116.
- Karthick, B., Mahesh, M.K. & Ramachandra, T.V. 2011. Nestedness pattern in stream diatom assemblages of central Western Ghats. *Current Science* **100**: 552–558.
- Karthick, B., Taylor, J.C., Mahesh, M.K. & Ramachandra, T.V. 2010. Protocols for Collection, Preservation and Enumeration of Diatoms from Aquatic Habitats for Water Quality Monitoring in India. *The IUP Journal of Soil and Water Sciences* **3(1)**: 1–36.
- Kelly, M.G., Cazaubon, A., Coring, E., Dell'Uomo, A., Ector, L., Goldsmith, B., Guasch, H., Hürlimann, J., Jarlman, A., Kawecka, B., Kwadrans, J., Laugaste, R., Lindström, E.A., Leitao, M., Marvan, P., Padisák, J., Pipp, E., Prygiel, J., Rott, E., Sabater, S., van Dam, H. & Vizinet, J. 1998. Recommendations for the routine sampling of diatoms for water quality assessments in Europe. *Journal of Applied Phycology* **10**: 215–224.
- Kociolek, J.P. & Kingston, J.C. 1999. Taxonomy, ultrastructure, and distribution of some gomphonemoid diatoms (Bacillariophyceae: Gomphonemataceae) from rivers in the United States. *Canadian Journal of Botany* **77**: 686–705.
- Krammer, K. & Lange-Bertalot, H. 1991a. Bacillariophyceae 3. Teil : Centrales, Fragilariaceae, Eunotiaceae. 576 pp. *In*: Ettl, H., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds) *Süßwasserflora von Mitteleuropa* **2/3**. Gustav Fischer, Jena.
- Lange-Bertalot, H. 2001. *Navicula* sensu stricto, 10 genera separated from *Navicula* sensu lato, *Frustulia*. 526 pp. *In*: Lange-Bertalot, H. (ed.) *Diatoms of Europe: Diatoms of the European inland waters and comparable habitats* **2**. A.R.G. Gantner, Ruggell.
- Leira, M. & Cantonati, M. 2008. Effects of water-level fluctuations on lakes: an annotated bibliography. *Hydrobiologia* **613**: 171–184.
- Liancourt, P., Callaway, R.M. & Michalet, R. 2005. Stress tolerance and competitive-response ability determine the outcome of biotic interactions. *Ecology* **86**: 1611–1618.
- Müller, B. & Gächter, R. 2012. Increasing chloride concentrations in Lake Constance: Characterization of sources and estimation of loads. *Aquatic Sciences* **74**: 101–112.
- Poulíčková, A., Dokulil, M. & Duchoslav, M. 2004. Littoral diatom assemblages as bioindicators of lake trophic status: A case study from perialpine lakes in Austria. *European Journal of Phycology* **39**: 143–152.
- Ramachandra T.V. & Kumar U. 2008. Spatial Decision Support System for Land Use Planning. *The Icfai University Journal of Environmental Science* **2(3)**: 7–19.
- Ramachandra, T.V., Setturu, B. & Aithal, B.H. 2012. Peri-Urban to Urban Landscape Patterns Elucidation through Spatial Metrics. *International Journal of Engineering Research and Development* **2(12)**: 58–81.
- Sharma, A., Kumar, K., Prasad, V. & Thakur, B. 2011. Diatom distribution and its relationship with water quality in the Mahi River Basin. *Current Science* **101**: 1011–1015.
- Solak, C.N. & Acs, E. 2011. Water Quality Monitoring in European and Turkish Rivers Using Diatoms. *Turkish Journal of Fisheries and Aquatic Sciences* **11**: 329–337.
- Stenger-Kovács, C., Padisák, J., Hajnal, É. & Buczkó, K. 2007. Epiphytic, littoral diatoms as bioindicators of shallow lake trophic status: Trophic Diatom Index for Lakes (TDIL) developed in Hungary. *Hydrobiologia* **589**: 141–154.
- Sudhira, H.S., Ramachandra, T.V. & Balasubramanya, M.H. 2007. City profile: Bangalore. *Cities* **124**: 379–390.
- Taylor, J.C., Prygiel, J., Vosloo, A., de la Rey, P.A. & Van Rensburg, L. 2007a. Can diatom-based pollution indices be used for biomonitoring in South Africa? A case study of the Crocodile West and Marico water management area. *Hydrobiologia* **592**: 455–464.
- Taylor J.C., Archibald C.G.M. & Harding W.G. 2007b. A methods manual for the collection, preparation and analysis of diatom samples. WRC Report No TT 281/07. Water Research Commission, Pretoria. South Africa.
- ter Braak, C.J.F. 1986. Canonical correspondence analysis: a new eigenvector method for multivariate direct gradient analysis. *Ecology* **67**: 1167–1179.
- Van Dam, H., Mertens, A. & Sinkeldam, J. 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Neetherlands. *Neetherlands Journal of Aquatic Ecology* **28**: 117–133.
- Walker, C.E. & Pan, Y. 2006. Using diatom assemblages to assess urban stream conditions. *Hydrobiologia* **516**: 179–189.
- Walsh, G. & Wepener, V. 2009. The influence of land use on water quality and diatom community structures in urban and agriculturally stressed rivers. *Water SA* **35**: 580–595.
- Wang, Q., Yang, X., Hamilton, P.B. & Zhang, E. 2012. Linking spatial distributions of sediment diatom assemblages with hydrological depth profiles in a plateau deep-water lake system of subtropical China. *Fottea* **12**: 59–73.
- Winter, J.G. & Duthie, H.C. 2000. Stream biomonitoring at an agricultural test site using benthic algae. *Canadian Journal of Botany* **78**: 1319–1325.
- Wojtal, A.Z., Lange-Bertalot, H., Nautiyal, R., Verma, J. & Nautiyal, P. 2010. *Achnantheidium chitrakootense* spec. nov. from rivers of Northern Central India. *Polish Botanical Journal* **55**: 55–64.

Annexure 1: List of names of wetlands analyzed in the study for water quality and diatom assemblages *(Codes and site number with reference to Figure 4, DCCA plot)

WETLANDS	CODE	SITE#
Sankey	SN	82,83
Ulsoor	US	86,87
Valley school	VL	58,59
Belandur	BL	47,48
Doddanekundi	DK	94,95
Hebbal	HB	84,85
ISRO layout	IR	56,57
Jakkur	JK	1-3
Kothanur	KT	20-22
Madiwala	MD	62-64
Mallathalli	ML	15,16
Rachenahalli	RC	4-8
Subramanyapura	SB	54,55
Venkateshpura	VN	9-11
Anchepalya	AC	41,42
Begur	BG	92,93
Chikbanavara	CI	65
Doddabidarekallu	DB	105
Hulimavu	HL	72,73
Kammagondanahalli	KO	96,97
Kannur	KA	101,102
Kommaghatta	KM	12-14
Konasandra	KN	31-35
Malsandra	MS	78,79
Narasappanahalli	NR	74,75
Ramasandra	RM	36-40
Rampura	RP	99,100
Somapura	SM	27-30
Thalghattapura	TA	23-26
Thirumenahalli	TI	69,71
Tigudarapalya	TG	80,81
Ullalu	UL	17-19
Varthur	VR	49,50
Vengayyanakere	VG	76,77
Yalamallappachetty	YL	51-53
Yelahanka	YE	103,104
Hennagara	HN	88,89
Hesaraghatta	HG	106
Hoskere	HS	43-46
Muthanallur	MT	90,91
Nelakondoddi	NL	66-68
Rayasandra	RY	98
Vaderahalli	VD	60,61

Annexure 2: List of 41 diatom species with relative abundance more than 10% with code names

NAME OF THE DIATOM TAXA	CODES
<i>Achnantheidium exiguum</i> (Grunow) Czarn.	AEHE
<i>Achnantheidium</i> sp.	ACHD
<i>Amphora coffeaeformis</i> (C.Agardh) Kütz.	ACAC
<i>Amphora veneta</i> Kütz.	AVEN
<i>Amphora</i> sp.	AVCA
<i>Aulacoseira ambigua</i> (Grunow) Simonsen	AAMB
<i>Aulocoseira granulata</i> (Ehrenb.) Simonsen	AGCU
<i>Bacillaria paradoxa</i> J.F.Gmel.	BPAR
<i>Brachysira neoexilis</i> (Grunow) D.G.Mann	BNEO
<i>Cyclotella atomus</i> Hust.	CATO
<i>Cyclotella meneghiana</i> Kütz.	CMEN
<i>Cyclotella ocellata</i> Pant.	COCE
<i>Cymbella turgidula</i> Grunow	CYMG
<i>Cymbella kappi</i> (Cholnoky) Cholnoky	CYMB
<i>Diademsis confervacea</i> Kütz.	DCOF
<i>Diploneis oblongella</i> (Nägeli) Cleve-Euler	DOBL
<i>Diploneis subovalis</i> Cleve	DSUB
<i>Encyonopsis microcephala</i> (Grunow) Krammer	EMCR
<i>Eolimna subminuscula</i> (Manguin) G.Moser <i>et al.</i>	ESBM
<i>Fragilaria biceps</i> (Kütz.) Lange-Bert.	FBCP
<i>Fragilaria ulna</i> var. <i>acus</i> (Kütz.) Lange-Bert.	FAUT
<i>Gomphonema spiculoides</i> H.P.Gandhi	GOMPL
<i>Gomphonema angustum</i> C.Agardh	GANG
<i>Gomphonema gracile</i> Ehrenb.	GGRA
<i>Gomphonema</i> sp. 1	GOMPP
<i>Gomphonema</i> sp. 3	GOMP3
<i>Gomphonema parvulum</i> Kütz.	GPAP
<i>Gyrosigma rautenbachiae</i> Cholnoky	GRAU
<i>Navicula cryptotenella</i> Lange-Bert.	NAVIB
<i>Navicula gregaria</i> Donkin	NGRE
<i>Navicula symmetrica</i> Patrick	NSYM
<i>Navicula veneta</i> Kütz.	NVEN
<i>Nitzschia williamsii</i> Alakananda <i>et al.</i>	NITZ
<i>Nitzschia amphibia</i> Grunow	NAAC
<i>Nitzschia gracilis</i> Hantz.	NGLS
<i>Nitzschia linearis</i> (C. Agardh) W.Sm.	NLIN
<i>Nitzschia palea</i> (Kütz.) W.Sm.	NPAL
<i>Nitzschia umbonata</i> (Ehrenb.) Lange-Bert.	NUMB
<i>Rophalodia gibba</i> (Ehrenb.) O. Müll.	RGIB
<i>Seminavis strigosa</i> (Hust.) Danielidis <i>et Econ.-Amilli</i>	SMNA
<i>Staurosirella pinnata</i> (Ehrenb.) Williams <i>et Round</i>	SPIN