Chapter 3

Application of Diatom-Based Indices in River Quality Assessment: A Case Study of Lower Ogun River (Abeokuta, Southwestern Nigeria) Using Epilithic Diatoms

Adewole Michael Gbadebo,
Benjamin Onozeyi Dimowo,
Adewale Matthew Taiwo and Isaac Tunde Omoniyi

Additional information is available at the end of the chapter

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Abstract

Diatom indices have been extensively applied in the bioassessment of surface waters and wetlands in many countries except Nigeria. This pioneer study aimed at investigating the use of epilithic diatom-based indices in the assessment of the Ogun River quality. Water and epilithic diatom samples were collected fortnightly from four sampling stations for a period of four consecutive months (March–June 2015). Water samples were analysed for pH, temperature, electrical conductivity, total dissolved solids (TDS), dissolved oxygen, chemical oxygen demand (COD), nitrite, nitrate, ammonium, phosphate, sulphide, chloride, iron, manganese, silicate, total alkalinity, total hardness, total suspended solids (TSS), transparency and total organic carbon using standard methods. Epilithic diatom samples were collected by scraping the surfaces of rocks or stones using an 18 mm toothbrush and analysed following the standard methods. Data collected were subjected to descriptive (frequency, mean) and inferential statistics (diatom indices, Pearson correlation) using OMNIDIA and SPSS statistical packages. Results showed that the water quality of the Lower Ogun River ranged between bad and high qualities during the study period. The diatom indices (trophic diatom index (TDI), biological diatom index (IBD), generic salinity index (GSI1), generic trophic index (GTI), generic saprobity index (GTI)) were correlated with physical and chemical parameters, thereby indicating their effectiveness in water quality ranking.

Keywords: environmental management, applied ecology, ecosystem health, water quality assessment, surface water bioindicators

1. Introduction

Diatom-based indices are increasingly becoming important tools for the assessment of ecological conditions in lotic and lentic systems [1], and the ability to use diatoms to evaluate present and past conditions of water quality and environmental change in just about any aquatic environment has been recognized worldwide for many decades [2–6].

They are well favoured than other aquatic bioindicators in use during water quality assessment due to their cosmopolitan distribution and well-known ecological requirements. These features enable diatom indices developed in a geographic region to be used in other parts of the world [7]. This explains their wide usage in various water bodies in the world.

Some of the diatom indices in use presently include Descy's index or DES [8], Sládecek's index or SLA [9], Leclercq and Maquet's index or LMI [10], the Watanabe index or WAT [11], the Commission of Economical Community Index or CEC [12], Schiefele and Schreiner's index or SHE [13], Rott's index or ROT [14], the generic diatom index or GDI [15], the Specific Pollution Sensitivity Index or SPI [16], the biological diatom index or IBD [17], the eutrophication/pollution index or EPI [18], the Artois-Picardie Diatom Index or APDI [19], the trophic diatom index or TDI [20], the Pampean Diatom Index or IDP [21] and the South African Diatom Index [22].

These indices according to Taylor et al. [23] function in the following manner: in a sample from a body of water with a particular level of determinant (e.g. salinity), diatom taxa with their optimum close to that level will be the most abundant. Therefore an estimate of the level of that determinant in the sample can be made from the average of the optima of all the taxa in that sample, each weighted by its abundance. A further refinement is the provision of an indicator value which is included to give greater weight to those taxa which are good indicators of particular environmental conditions. In practice, the first step to be completed when using diatom indices is the compilation of a list of taxa in a sample, together with their absolute abundance. The final index value is expressed as the mean of the optima of the taxa in the sample, weighted by the abundance of each taxon. The indicator value acts to further increase the influence of certain species [23, 24].

All these indices are based on the formula of Zelinka and Marvan [25] except the CEC, SHE, TDI and WAT indices [23]. The quality of running rivers has been successfully classified using epilithic diatom-based indices in Bulgaria [26].

Diatom indices have also been utilized in monitoring biotic integrity and trophic condition of aquatic ecosystems in select countries in sub-Saharan Africa [27] which include South Africa [28–35], Kenya [36–39], Zimbabwe [40, 41] and Zambia [42].

However, such studies have not been carried out on Nigerian water bodies. The Ogun River is a perennial water source which passes through areas of high population density [43–45]. In populated areas, river water quality is determined by human practices: deforestation, farming, industrial and domestic sewage discharge, which cause changes in colour, suspended solids, pH, temperature, nutrients and run-off characteristics [46].

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Being that diatom-based biomonitoring programmes have been implemented with some success in South Africa, Kenya, Zimbabwe and Zambia [27], this study therefore investigated the use of epilithic diatom-based indices in water quality assessment of the Lower Ogun River.

2. Materials and methods

2.1. Description of the study area

Abeokuta is the capital and the largest city in Ogun State which is situated in the southwestern part of Nigeria [47]. Soils in Abeokuta have been characterized as being sandy, formed from sedimentary rocks, and can only support savannah vegetation. Vegetation is predominated by guinea and derived savannah [48]. The Ogun River (**Figure 1**) is one of the main rivers in the southwestern part of Nigeria with a total area of 22.4 km^2 and a fairly large flow of about 393 m^3 s^{-1} during the wet season [49]. It has coordinates of 3028″E and 8041″N from its source in Oyo State to 3025″E and 6035″N in Lagos where it enters the Lagos lagoon [43]. Mean annual rainfall ranges from 900 in the north to 2000 mm towards the south. The estimates of total annual potential evapotranspiration have been put between 1600 and 1900 mm [50]. The Ogun River water is used for agriculture, transportation, human consumption, various industrial activities and domestic purposes [43, 49]. It also serves as a

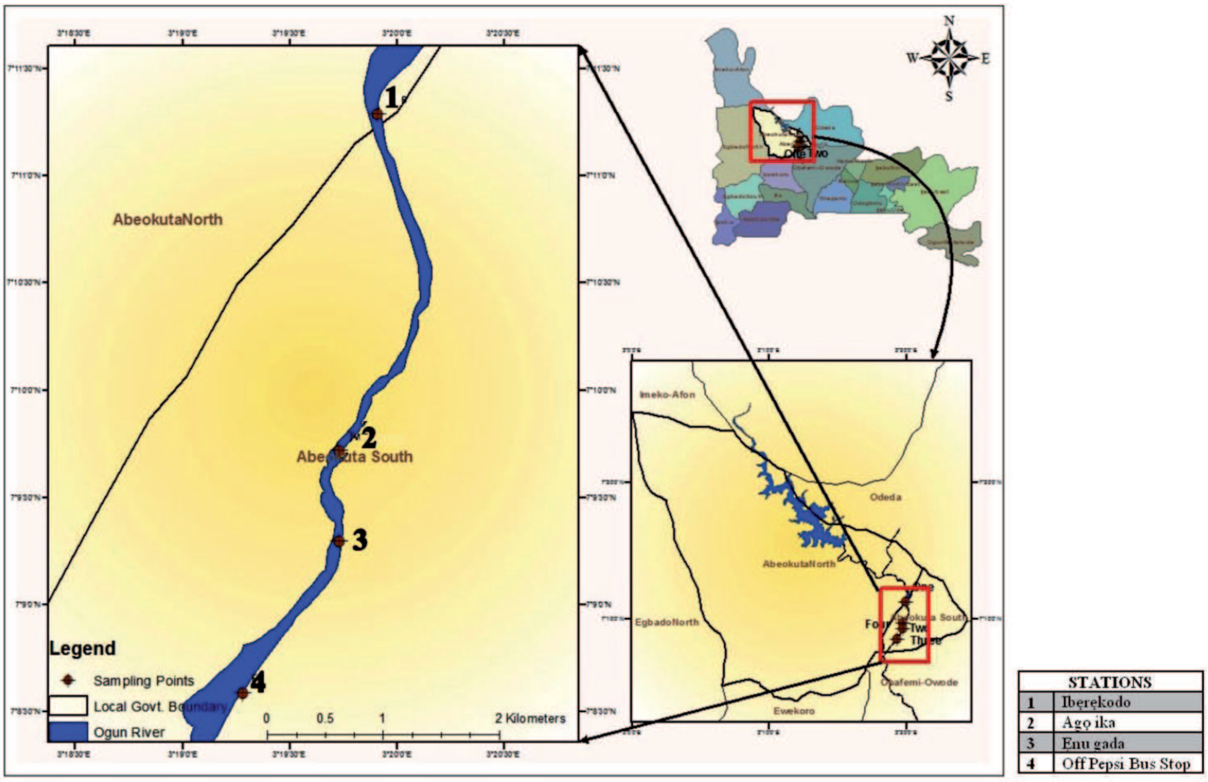

Figure 1. Map of Lower Ogun River, Abeokuta showing the sampling station.

raw material to the Ogun State Water Corporation which treats it before dispensing it to the public. Along its course, it constantly receives effluents from breweries, slaughterhouses, dyeing industries, tanneries and domestic wastewater before finally discharging to Lagos lagoon [43, 45, 49].

Reports on the water quality of the Ogun River have been documented for over 30 years [51, 52]. Several studies have been reported on the water quality of the lower part of the Ogun River at Abeokuta. Among such studies (**Table 1**) include Ojekunle et al. [53], Adeosun et al. [54], Taiwo et al. [55], Olayinka et al. [56], Ikotun et al. [57], Awoyemi [58], Dimowo [44, 45], Osunkiyesi [59] and Adeogun et al. [60].

2.2. Water sampling and analysis procedure

Water samples were collected into well-labelled sample bottles fortnightly for the period of 4 months (March–June 2015) from four sampling stations along the river. Station A was located close to the Ogun State Water Corporation, Arakanga, Ibẹ̀rẹ̀kodo; Station B was located close to the FADAMA III supported ferry at Agọ Ika; Station C was located just below the bridge connecting to Lafenwa at Ẹnu Gada; and Station D was located just down the road of Pepsi bus stop, Quarry Road. The physical and chemical parameters determined included pH, water temperature, electrical conductivity and total dissolved solids which were determined in situ with the use of HANNA Hi 98129 multimeter, while dissolved oxygen, chemical oxygen demand, nitrite, nitrate, ammonium, phosphate, sulphide, chloride, iron, manganese, silicate, total alkalinity, hardness, total suspended solids and total organic carbon were determined in the laboratory using standard methods [61]. Water transparency was also measured in situ using a Secchi disc.

2.3. Epilithic diatom sampling and analysis procedure

Diatom samples were collected fortnightly from four sampling stations along the river for the period of 4 months (March–June 2015). The surfaces of the rocks or stones were scraped off using an 18 mm toothbrush. The brushed areas of the stones, as well as the toothbrush covered with algae, were flushed into a plastic bowl with water. The obtained brown or greenish suspension containing the diatoms was collected and preserved with neutral formaldehyde (4%) to prevent the silica cell walls from cracking. Due to the unavailability of rocks/stones at sampling stations at certain visits, other submerged substrates such as wood material were sampled. This method was adapted from the recommendations of Martin and Fernandez [62] and Kelly et al. [63]. Thereafter, in the laboratory, the samples were mounted on microscope slides by first shaking the samples vigorously and then pipetting a drop onto the slides with the use of a dropper. The identification of the diatoms was done to the lowest taxonomic category possible under the microscope using keys of identification such as [64–67]. Then enumeration was carried out using the drop count method adapted from Dhargalkar and Ingole [68]. The abundance of organisms in each sample was extrapolated from the number of organisms per drop to the number of organisms per ml by multiplying the number of organisms per drop by 20 based on the tested premise that 20 drops of the sample make 1 ml.

Parameters	Present study	Ojekunle et al. [53]	Adeosun et al. [54]	Taiwo et al. [55]	Olayinka et al. [56]	Ikotun et al. [57]	Awoyemi [58]	Dimowo [44]	Osunkiyesi [59]	Adeogun et al. [60]
W-T (°C)	25.85–32.3	24.3–27.5	24–30.7	26.8–27	27.87–29.5	23.7–31.7	29–31	26.9–32.1	27–32	24.5–32
TRANS (cm)	14–88.75	NA	53–100	NA	NA	NA	98–173	20–70	NA	NA
COND (μScm^{-1})	127–377	NA	140–190	103.7–105	412.67–514.67	NA	150–388	99–180.5	NA	725.19–3400
TDS (mgL^{-1})	63.5–189	690–7000	70–95	46–48	93.33–95	NA	75–194	48.8–90.8	438–448	346.05–757.03
NO_3^- (mgL^{-1})	0.02–47.5	35–205	0.235–5.445	0.4–0.9	1.85–2.13	0.66–3.91	20.49–63.42	0.6–113.4	NA	12.28–89.43
NO_2^- (mgL^{-1})	0.03–0.4	NA	NA	NA	NA	NA	NA	NA	0.65–0.69	NA
PO_4^- (mgL^{-1})	1.75–28	52–250	0.02–0.75	NA	2.68–3.26	0.19–2.0	0.035–0.583	0–0.1	NA	1.85–18.62
DO (mgL^{-1})	5.51–6.72	0.1–8.82	4.12–5.32	5.5–6.0	3.7–4.75	3.9–7.7	1.88–5.52	2.8–7.7	NA	0–11.27
COD (mgL^{-1})	4–678.5	350–2500	NA	NA	88.33–111.67	NA	NA	NA	NA	181.5–1374.91
pH	8.36–9.91	6.14–7.3	7.45–9.73	7.92–7.96	6.37–7.1	6.5–7.7	6.5–7.95	7.7–9.1	7.6–7.72	5.5–8.8
TSS (mgL^{-1})	0–49	NA	NA	79–95	2.79–5.32	52.9–107.5	NA	NA	446.00–448.09	822.93–1495.47
TA (mgL^{-1})	3.75–10	NA	4.5–14.5	0.1–0.1	NA	NA	NA	4.4–17.8	42.9–43.6	NA
TH (mgL^{-1})	2.6–7.15	NA	NA	41–50	NA	NA	NA	45.5–105	36.1–38.1	NA
Cl^- (mgL^{-1})	25–25	380–1990	NA	NA	NA	29.3–104.5	NA	NA	8.98–9.86	15.33–183.58
Fe^+ (mgL^{-1})	0.05–1.53	NA	NA	0.3–0.4	1.37–1.73	0.12–2.3	NA	NA	13,800–16,100	NA
Mn^+ (mgL^{-1})	0.03–0.66	NA	NA	NA	NA	0–1.0	NA	NA	289–466	NA

W-T = water temperature; pH = hydrogen ion concentration; COND = electrical conductivity; TDS = total dissolved solids; TRANS = water transparency; Fe^+ = iron; NO_2^- = nitrite; NO_3^- = nitrate; Mn^+ = manganese; SiO_3^- = silicate; PO_4 = phosphates; Cl^- = chloride; TA = total alkalinity; TH = total hardness; COD = chemical oxygen demand; TSS = total suspended solids; DO = dissolved oxygen

Table 1. Reports on the water quality of the Lower Ogun river at Abeokuta.

2.4. Statistical analysis

Descriptive statistics in the form of frequency tables and range were used in the presentation of the data. Inferential statistics such as diatom indices, viz. biological diatom index (IBD), trophic diatom index, (TDI) and generic diatom indices (GDI) (saprobity index, trophic index and salinity index) were utilized in determining the water quality status of the Ogun River. IBD was calculated using OMNIDIA free version software [69], while TDI and GDI were calculated using MS Excel spreadsheets [70] following the method adapted from Kelly et al. [20] and Van Dam [71], respectively.

2.4.1. Correlation analysis

Bivariate correlation analysis was carried out using Pearson's product moment coefficient of correlation in SPSS to check for the relationship between the physical and chemical parameters and diatom indices. The physical and chemical parameters (except pH) and diatom abundance data were log transformed before analysis in order to achieve normal distribution.

2.4.2. Ranking of water quality using diatom-based indicators

According to Taylor et al. [23], diatom-based indicators in all cases are calculated using the formula of Zelinka and Marvan [25] except for the Commission of Economical Community Index (CEC), Schiefele and Schreiner's index (SHE), trophic diatom index (TDI) and Watanabe index (WAT index). They have the basic form [4] given:

$$\text{index} = \frac{\sum_{j}^{a} = 1^{a_j s_j v_j}}{\sum_{j}^{a} = 1^{a_j v_j}} \quad (1)$$

where a_j is the abundance (proportion) of species j in sample; s_j is the pollution sensitivity of species j; v_j is the indicator value.

The performance of the indices depends on the values given to the constants s and v for each taxon, and the values of the index range from 1 to an upper limit equal to the highest value of s.

Index score	Water quality rank	Trophic status
>17	High quality	Oligotrophy
15–17	Good quality	Oligo-mesotrophy
12–15	Moderate quality	Mesotrophy
9–12	Poor quality	Mesoeutrophy
<9	Bad quality	Eutrophy

Source: Adapted from [73]

Table 2. Water quality ranking with the use of IBD.

Diatom indices differ in the number of species used and in the values of s and v which have been attributed after compiling the data from literature and from ordinations [4, 72]. For all of the above indices, except TDI (maximum value of 100), the maximum value of 5 (converted to 20 by the software package OMNIDIA) indicates a high quality or pristine water resource [23].

The diatom biotic indices, viz. IBD, TDI and GDI, were interpreted following the classifications in **Tables 2–4** as adapted from Kelly et al. [20] and Van Dam [71], Eloranta and Soininen [73] and Delta Environmental [74].

<table>
<tr><td></td><td></td><td colspan="4">Percentage of motile valves</td><td rowspan="2">Interpretation</td><td rowspan="2">Remarks</td></tr>
<tr><td></td><td></td><td><20%</td><td>21 – 40%</td><td>41 – 60%</td><td>>60%</td></tr>
<tr><td rowspan="5">TDI Range</td><td>0 – 9
10 – 19</td><td></td><td></td><td></td><td></td><td rowspan="5">A vertical movement on the chart indicates a change in water quality due to nutrients while a horizontal movement indicates change due to other factors.</td><td>Oligotrophic
Fairly oligotrophic</td></tr>
<tr><td>20 – 29
30 – 39</td><td></td><td></td><td></td><td></td><td>Oligo-mesotrophic
Highly oligo-mesotrophic</td></tr>
<tr><td>40 – 49
50 – 59</td><td></td><td></td><td></td><td></td><td>Fairly mesotrophic
Mesotrophic</td></tr>
<tr><td>60 – 69
70 – 79</td><td></td><td></td><td></td><td></td><td>Meso-eutrophic
Fairly eutrophic</td></tr>
<tr><td>80 – 89
≥90</td><td></td><td></td><td></td><td></td><td>Eutrophic
Highly eutrophic</td></tr>
</table>

Source: Adapted from [20]

Table 3. TDI water quality lookup chart.

Generic salinity index	Generic trophic index	Generic saprobity index	Water quality classes	Index score
Very clean	Oligotrophic	Oligosaprobous	I	>1
Clean	Oligo-/mesotrophic	β-Mesosaprobous	II	1–0.96
Moderate	Mesotrophic	α-Mesosaprobous	III	0.95–0.76
Polluted	Eutrophic	Meso-/polysaprobous	IV	0.75–0.56
Very polluted	Hypereutrophic	Polysaprobous	V	<0.56

Source: Based on [71, 74]

Table 4. Interpretation of generic diatom indices.

3. Results

The weekly and monthly spatial variation in the physical and chemical parameters and the weekly variation in the epilithic diatom abundance and epilithic diatom indices of the Ogun River at Abeokuta are available as supplementary files.

3.1. Epilithic diatom composition and variation

A total of 61 epilithic diatoms (**Table 5**) belonging to 12 orders and 3 classes were identified in the study sites. *Caloneis bacillum* (3600 cells mL^{-1}) had the highest total count followed by *Coscinodiscus rothii* (2300 cells ml^{-1}) and *Campylodiscus clypeus* (1780 cells mL^{-1}).

The monthly spatial variation in epilithic diatom indices (**Table 6**) was in the following order: Trophic diatom index was found highest in March (69.26; Station C) and lowest in June (14.52; Station C). %Motile taxa was found highest in June (31.42; Station D) and lowest in April (1.10; Station B). Biological diatom index was found highest in June (15.10; Station D) and lowest in June (7.75; Station A). Generic salinity index (GSI1) was found highest in May (20.00; Station B). It was lowest in March, April (0.00; Station C) and June (0.00; Stations B, C, D). Generic trophic index was found highest in June (9.00; Station B) and lowest in June (0.00; Stations C and D). Generic saprobity index was found highest in March (4.00; Station A) and lowest in April (0.08; Station D).

3.2. Water quality parameters

The physical and chemical parameters (**Table 1**) assessed in this study had the following ranges: Water temperature was found highest in May (32.3°C; Station A) and lowest in June (25.85°C; Station D). Water transparency was highest in April (88.75 cm; Station B) and lowest in June (14 cm; Station D). Electrical conductivity was highest in March (377 µS cm^{-1}; Station C) and lowest in March (127 µS cm^{-1}; Station B). Total dissolved solids was highest in March (189 mg L^{-1}; Station C) and lowest in March (63.5 mg L^{-1}; Station B). Nitrate was highest in April (47.5 mg L^{-1}; Station A) and lowest in May (0.02 mg L^{-1}; Station A). Nitrite was highest in March (0.4 mg L^{-1}; Station D) and lowest in June (0.03 mg L^{-1}; Stations A, B and C). Phosphate was highest in April (28 mg L^{-1}; Station C) and lowest in June (1.75 mg L^{-1}; Station D). Dissolved oxygen was highest in June (6.72 mg L^{-1}; Station D) and lowest in March (5.51 mg L^{-1}; Station A). Chemical oxygen demand was found highest in June (678.5 mg L^{-1}; Station D) and lowest in June (4 mg L^{-1}; Station C). pH was highest in April (9.91; Station A) and lowest in March (8.36; Station B). Total suspended solids was highest in May (49 mg L^{-1}; Station D) and lowest in May (0 mg L^{-1}; Station A). Total alkalinity was highest in June (10 mg L^{-1}; Station D) and lowest in March (3.75 mg L^{-1}; Station C). Total hardness was highest in March (7.15 mg L^{-1}; Station D) and lowest in March (2.6 mg L^{-1}; Station A). Chloride levels were constant throughout the study period (25 mg L^{-1}). Iron was found highest in April (1.53 mg L^{-1}; Station C) and lowest in June (0.05 mg L^{-1}; Station A). Manganese was highest in May (0.66 mg L^{-1}; Station D) and lowest in May (0.03 mg L^{-1}; Station B).

Epilithic diatom species	March 2015				April 2015				May 2015				June 2015				Total count
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	
Melosira varians	—	680	—	—	—	80	20	640	—	120	80	120	—	—	—	20	1760
Aulacoseira granulata	—	40	—	—	300	60	20	60	100	20	220	200	160	100	20	—	1300
Cyclotella meneghiniana	—	—	40	—	60	60	40	—	340	—	—	80	100	20	100	20	860
Cyclotella stelligera	—	240	—	—	—	—	—	—	40	—	—	—	—	—	—	240	520
Coscinodiscus rothii	—	—	80	—	240	120	100	700	220	60	—	100	160	—	340	180	2300
Stephanodiscus margarae	—	—	—	—	—	—	—	—	60	60	—	20	60	—	100	—	300
Stephanodiscus agassizensis	—	—	60	—	—	1160	40	—	180	100	60	100	—	—	—	—	1700
Cyclostephanos tholiformis	—	—	—	—	—	—	—	—	—	40	—	20	—	—	—	—	60
Fragilaria capucina	40	—	—	220	—	—	20	—	—	—	—	20	—	—	—	—	300
Synedra acus	—	—	—	—	—	20	—	—	—	—	—	20	140	—	60	40	280
Synedra nana	—	—	—	—	—	—	—	—	—	—	—	—	20	—	—	20	40
Synedra ulna	60	1140	40	80	160	40	—	80	—	140	220	40	80	40	40	120	2280
Diatoma vulgaris	—	—	100	40	—	—	—	—	—	—	—	—	—	20	—	—	160
Diatoma hiemale	40	—	—	40	—	—	—	—	—	100	20	40	—	—	—	—	240
Diatoma tenuis	—	80	60	40	140	80	100	100	60	20	60	—	—	—	—	—	740
Staurosira construens	—	—	—	—	—	—	—	—	—	—	—	—	60	—	—	—	60
Meridion circulare	—	—	—	—	40	—	—	—	—	40	20	—	—	—	—	—	100
Tetracyclus lacustris	—	20	—	—	—	—	—	—	—	—	—	40	—	—	220	60	340
Cymbella tumida	—	—	—	—	—	—	20	—	20	—	40	20	—	—	—	—	100
Gomphonema parvulum	—	—	—	—	—	—	—	—	—	—	—	—	—	20	—	—	20
Gomphonema acuminatum	—	—	—	—	—	—	—	—	—	—	—	—	20	—	—	—	20
Gomphonema truncatum	—	—	—	—	—	—	—	20	20	—	20	—	—	—	—	—	60

Epilithic diatom species	March 2015				April 2015				May 2015				June 2015				Total count
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	
Asterionella formosa	60	—	—	—	—	—	—	—	40	—	—	—	—	—	20	—	120
Amphicampa erura	—	—	—	—	—	—	—	—	40	—	—	20	—	—	—	—	60
Eunotia serpentine	60	—	—	—	20	—	—	—	—	40	160	—	—	60	20	—	360
Eunotia formica	20	80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	100
Eunotia bilunaris	—	—	—	—	40	—	—	—	20	—	—	—	—	—	—	—	60
Gyrosigma cf. *scalproides*	20	—	—	—	—	—	—	—	—	—	—	—	—	—	20	—	40
Gyrosigma attenuatum	140	240	—	20	60	—	—	—	20	—	—	—	40	40	—	—	560
Navicula viridula	—	—	—	—	—	—	—	—	—	—	—	—	—	40	60	—	100
Navicula radiosa	20	500	—	—	—	—	—	—	—	—	—	—	—	—	—	20	540
Navicula capitoradiata	140	—	200	—	—	—	—	—	—	—	—	—	—	—	—	—	340
Navicula cryptocephala	20	140	120	—	—	—	20	—	—	—	—	—	—	—	—	—	300
Navicula spp.	—	—	—	—	60	—	—	—	—	—	—	—	—	—	—	—	60
Navicula cf. *margalithi*	—	280	380	—	—	—	—	—	—	—	—	—	—	—	—	—	660
Pinnularia viridis	40	140	—	40	260	—	—	—	180	320	—	—	—	—	—	—	980
Pinnularia cf. *interrupta*	20	40	—	—	60	—	40	—	40	20	40	20	—	—	—	—	280
Frustulia vulgaris	—	—	—	—	—	20	—	—	40	—	40	120	20	60	80	420	800
Sellaphora pupula	—	—	20	—	—	—	—	—	—	—	—	—	—	—	—	—	20
Sellaphora seminulum	—	—	—	—	—	40	—	20	—	—	—	—	—	—	—	—	60
Sellaphora bacillum	—	—	—	20	20	60	—	—	—	—	—	—	—	—	—	—	100
Stauroneis cf. *kriegerii*	—	—	20	—	—	—	40	—	—	—	—	—	—	—	—	—	60
Caloneis bacillum	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3600	3600
Craticula cuspidata	—	140	—	—	—	—	—	—	—	—	—	—	—	—	—	—	140

Epilithic diatom species	**March 2015**				**April 2015**				**May 2015**				**June 2015**				**Total count**
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	
Achnanthes lanceolata	40	—	20	40	—	—	—	—	—	—	—	80	40	—	—	—	220
Planothidium lanceolatum	—	—	—	—	—	—	—	—	—	—	—	20	—	—	—	—	20
Achnanthes cf. *inflate*	—	—	—	—	—	—	—	—	—	—	—	—	—	20	—	—	20
Cocconeis placentula	—	—	—	—	—	—	—	—	—	—	40	—	40	—	—	40	120
Nitzschia cf. *acicularis*	—	—	—	—	—	—	—	—	—	—	—	20	—	—	—	—	20
Nitzschia cf. *dissipata*	20	—	—	—	—	—	—	—	—	—	—	—	20	—	—	—	40
Nitzschia palea	180	180	—	60	40	—	—	100	—	—	—	—	—	—	—	—	560
Nitzschia intermedia	500	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	500
Bacillaria paradoxa	—	—	—	—	—	—	—	—	40	—	—	—	—	—	—	—	40
Cylindrotheca gracilis	—	—	—	—	—	—	20	—	—	—	—	20	—	—	—	—	40
Cymatopleura solea	—	—	—	—	—	—	20	—	—	—	—	—	—	—	—	—	20
Campylodiscus clypeus	80	—	—	—	120	60	—	20	80	—	200	200	520	80	420	—	1780
Rhopalodia gibba	—	—	20	—	120	20	—	20	—	—	—	—	—	—	—	—	180
Epithemia adnata	—	—	—	—	—	—	—	—	—	—	20	—	20	—	60	—	100
Epithemia sorex	—	—	—	—	—	—	—	—	—	—	—	—	—	—	180	—	180
Denticula subtilis	—	—	—	—	—	—	—	—	40	—	—	—	—	—	60	20	120
Amphora veneta	20	—	—	—	40	20	—	—	40	20	40	—	—	—	—	—	180

Table 5. Monthly spatial variation in the count of epilithic diatoms of the Ogun River in Abeokuta (cells mL^{-1}).

Epilithic diatom indices	March 2015				April 2015				May 2015				June 2015			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
TDI	60.44	60.23	69.26	46.30	21.19	56.25	37.96	68.60	15.09	18.61	25.68	47.40	66.91	43.33	14.52	41.15
%Motile taxa	15.63	9.40	12.90	3.90	10.82	1.10	7.35	1.55	15.05	10.83	2.67	5.76	3.20	8.54	8.16	31.42
Interpretation	P	P	P	M	G	M	G	P	H	H	G	M	P	M	H	M
IBD	11.47	11.79	9.04	14.90	11.19	10.08	11.12	9.17	10.08	13.36	11.70	11.04	7.75	12.04	7.77	15.10
Interpretation	P	P	P	M	P	P	P	P	P	M	P	P	B	M	B	G
GSI1	0.25	1.67	0.00	1.33	8.50	3.00	0.00	0.80	9.50	20.00	12.00	17.00	11.00	0.00	0.00	0.00
Interpretation	B	H	B	H	H	H	B	M	H	H	H	H	H	B	B	B
GTI	0.24	1.15	0.25	0.44	3.09	0.60	1.20	0.30	3.60	2.86	2.88	5.67	3.33	9.00	0.00	0.00
Interpretation	B	H	B	B	H	P	H	B	H	H	H	H	H	H	B	B
GSI2	3.00	0.30	0.20	0.67	2.83	0.25	0.75	0.08	0.75	1.54	2.50	1.42	2.40	4.50	0.40	0.14
Interpretation	H	B	B	P	H	B	P	B	P	H	H	H	H	H	B	B

TDI = trophic diatom index; %MT = %motile taxa; IBD = biological diatom index; GSI1 = generic salinity index; GTI = generic trophic index; GSI2 = generic saprobity index; H = high quality; G = good quality; M = moderate quality; P = poor quality; B = bad quality

Table 6. Monthly spatial variation in the epilithic diatom indices of Ogun River, Abeokuta.

Parameters	TDI	%Motile taxa	IBD	GSI1	GTI	GSI2
LogWT	0.068	−0.416	−0.120	0.187	−0.298	−0.251
pH	−0.153	−0.295	−0.268	0.383	−0.003	0.161
LogCOND	0.055	0.341	−0.035	−0.301	−0.199	−0.073
LogTDS	0.081	0.372	0.003	−0.295	−0.196	−0.070
LogTRANS	−0.101	−0.495	−0.239	0.322	−0.098	−0.014
LogFe	0.261	−0.168	−0.041	−0.040	−0.148	−0.515*
$LogNO_2$	−0.205	−0.138	0.512*	0.362	−0.031	−0.146
$LogNO_3$	0.443	−0.228	−0.090	−0.554*	−0.488	−0.236
LogMn	0.404	−0.342	−0.233	0.025	0.132	−0.107
$LogNH_4$	0.206	−0.466	−0.046	−0.345	−0.394	−0.513*
$LogSO_3$	0.397	−0.376	−0.276	−0.206	−0.257	−0.333
$LogSiO_3$	0.508*	0.058	0.167	−0.470	−0.379	−00.069
$LogPO_4$	0.109	−0.322	0.033	0.013	−0.222	−0.240
LogCl	.[a]	.[a]	.[a]	.[a]	.[a]	.[a]
LogTA	−0.280	0.079	−0.038	0.098	0.182	0.281
LogTOC	−0.490	0.161	−0.015	0.229	0.363	0.221
LogTH	−0.089	−0.042	0.244	0.121	0.060	−0.502*
LogCOD	0.406	0.185	0.279	0.273	−0.106	−0.217
LogTSS	0.253	−0.099	−0.095	0.361	0.099	0.013
LogDO	−0.009	0.107	0.101	−0.133	−0.210	−0.400
TDI	1	−0.181	−0.187	−0.374	−0.206	−0.130
%Motile taxa	−0.181	1	0.429	−0.189	−0.162	−0.090
IBD	−0.187	0.429	1	0.034	0.033	0.067
GSI1	−0.374	−0.189	0.034	1	0.424	0.225
GTI	−0.206	−0.162	0.033	0.424	1	0.716**
GSI2	−0.130	−0.090	0.067	0.225	0.716**	1

*Correlation is significant at the 0.05 level (two-tailed).

**Correlation is significant at the 0.01 level (two-tailed).

LogWT = log water temperature; pH = hydrogen ion concentration; LogCOND = log electrical conductivity; LogTDS = log total dissolved solids; LogTRANS = log water transparency; LogFe = log iron; $LogNO_2$ = log nitrite; $LogNO_3$ = log nitrate; LogMn = log manganese; Log NH_4 = log ammonium; $LogSO_3$ = log sulphide; $LogSiO_3$ = log silicate; $LogPO_4$ = log phosphate; LogTA = log total alkalinity; LogTOC = log total organic carbon; LogTH = log total hardness; LogCOD = log chemical oxygen demand; LogTSS = log total suspended solids; LogDO = log dissolved oxygen; TDI = trophic diatom index; IBD = biological diatom index; GSI1 = generic salinity index; GTI = generic trophic index; GSI2 = generic saprobity index

Table 7. Pearson correlation coefficients of physical and chemical parameters and epilithic diatom indices of the Ogun River at Abeokuta.

3.3. Relationship between physical and chemical parameters and epilithic diatom indices

Table 7 shows the Pearson correlation coefficients of physical and chemical parameters and epilithic diatom indices of the Ogun River at Abeokuta. Physical and chemical parameters and epilithic diatom indices exhibited the following relationship pattern: trophic diatom index was positively correlated with silicate ($r = 0.508$; $p < 0.05$). Biological diatom index was positively correlated with nitrite ($r = 0.512$; $p < 0.05$). Generic salinity index was negatively correlated with nitrate ($r = -0.554$; $p < 0.05$). Generic trophic index was positively correlated with generic saprobity index ($r = 0.716$; $p < 0.01$). Generic saprobity index was negatively correlated with iron ($r = -0.515$; $p < 0.05$), ammonium ($r = -0.513$; $p < 0.05$) and total hardness ($r = -0.502$; $p < 0.05$).

4. Discussion

Diatoms have been shown through research to be used as alternative/supplementary means of water quality assessment due to the specific water quality tolerance each species portend [4, 75–76]. They are sensitive and strongly respond to physicochemical and biological changes [77]. More so, the use of diatoms in water quality assessment is cheaper than routine chemical analyses and directly shows the impact of pollution on the aquatic biota [23].

The range of values got from this study on the physical and chemical parameters was comparable with those reported by previous studies except for pH which was more basic and total hardness which was relatively lower than the range of values previously reported [44, 45, 53–60].

A total of 61 diatom species were identified in this study. *Caloneis bacillum* emerged with the highest total count (cells mL^{-1}) followed by *Coscinodiscus rothii* and *Campylodiscus clypeus*. The dominance of *Caloneis bacillum* has also been reported in Lake Tanganyika by Cocquyt [78]. *Caloneis bacillum* has been reported by Ali et al. [79] to be present in Upper Dilimi River in Jos. *Caloneis bacillum* has also been reported to be dominant by Compere [80] at the fourth sampling site of the Red Sea Hills in north-eastern Sudan.

Following the ecological indicator values reported by Van dam et al. [71], *Caloneis bacillum* occurs mainly in water bodies but is sometimes found in wet environments. It is a nitrogen-autotrophic taxa, tolerating very small amounts of organically bound nitrogen with fairly high oxygen requirements (>75% saturation). It is rarely found in large numbers in rivers [81]. *Caloneis bacillum* is alkaliphilous mainly occurring in fresh brackish waters with $pH > 7$, chloride levels <500 mg L^{-1} and salinity <0.9%. *Caloneis bacillum* is meso-eutraphentic and β-mesosaprobous, thereby falling under water quality class II [71]. It has also been reported to be ubiquitous [82].

The dominance of *Caloneis bacillum* in this study was therefore indicative of moderate pollution.

All the diatom indices (TDI, IBD, GSI1, GSI2, GTI) differed in their ranking of the water quality of the Lower Ogun River at Abeokuta. However, the generic diatom indices (GSI1, GSI2, GTI) were quite similar in their water quality ranking. This misalliance is explained by the global nature of indices, which try to evaluate the general state of water quality and not only the trophic degree [83, 84].

The trophic diatom index (TDI) showed that during the study period, the river water was in most cases poor and moderate (there was a tie in frequency of occurrence) in terms of quality. However, the biological diatom index (IBD) showed that the river water was in most cases moderate in terms of quality.

The generic salinity index (GSI1) showed that the river water was in most cases high in terms of quality during the study period. This salinity classification was calculated based on the tolerance of diatoms to salinity.

The generic trophic index (GTI) ranked the river water during the study period as being in most cases high in terms of quality. This trophic classification was calculated based on the tolerance of diatoms to the trophic state of the aquatic ecosystem. According to Naumann [85] as cited by Van dam et al. [71], variations in trophic state are usually as a result of variations in concentration of inorganic nitrogen and phosphorus compounds. There are however various concepts regarding trophic state. For this reason, water quality assessment based on trophic state was rather qualitative.

The generic saprobity index (GSI2) showed that the river water was in most cases high in terms of quality during the study period. The saprobity classification was calculated based on the indicator properties of diatoms to the presence of biodegradable organic matter and oxygen concentrations in the aquatic ecosystem [71].

Diatom species react distinctly to varying physical and chemical parameters. They are sensitive to change in nutrient concentrations, supply rates and silica/phosphate ratios. Each taxon has a specific optimum and tolerance for nutrients such as phosphate and nitrogen, and this is usually quantifiable [4].

The following deductions were made from the relationship between physical and chemical parameters and epilithic diatom indices: As trophic diatom index (TDI) scores increased, the concentration of silicates increased. This shows that the increases and decreases in concentration of silicates in the river water supported the concomitant increase and decrease in TDI scores. This result corroborated Reynolds [86] as cited by Gbadebo et al. [87] who observed that silica plays an important role in the ecology of aquatic systems as it is an essential element for diatom existence comprising 26–69% of its cellular dry weight. This study did not observe correlations between TDI and pH as observed by Tan et al. [88] in South-East Queensland River, Australia. This study did not also observe correlations between TDI and total phosphates as observed by Vilbaste [89].

It was observed that biological diatom index (IBD) increased as the concentration of nitrites increased. This shows that nitrite influenced the diatoms of the aquatic ecosystem which was evidenced in the IBD scores. Nitrites are one of the nutrients that favour the growth of diatoms.

This result was supported by Kalyoncu and Şerbetci [1] who reported significant correlations between IBD, dissolved oxygen, temperature, conductivity, ammoniacal nitrogen, nitrite nitrogen and phosphate phosphorus. This result was also corroborated by Vilbaste [89] who reported significant correlations of IBD with water temperature, pH, total phosphate, nitrite nitrogen and ammoniacal nitrogen. This study however did not observe correlations between IBD and pH as observed by Tan et al. [88] in Upper Han River, China.

The lack of significant relationship between TDI, IBD, electrical conductivity and total dissolved solids was supported by the observation of Eassa [90] who reported that TDI showed no significant correlation with any physicochemical parameters and/or percentages of eutrophic species. This however did not corroborate Solak et al. [91] who reported negative correlations between TDI, electrical conductivity and total dissolved solids.

The relative abundance of motile diatom taxa in this study did not exhibit significant relationship with the physical and chemical parameters.

The relationship between the generic salinity index (GSI1) scores and the concentration of nitrates in the river water signified that increases in nitrate contributed to reduction in GSI1 scores, whereas no significant relationship was observed between generic trophic index (GTI) scores and physical and chemical parameters except with generic saprobity index (GSI2) scores. Also, generic saprobity index (GSI2) scores decreased as iron, ammonium and total hardness increased but increased with increasing GTI scores.

These results show that there was a close relationship between physical and chemical parameters and diatom-based indices. This is agreed with Bere et al. [40] who applied the indices to urban streams in Zimbabwe. The lack of significant correlation observed between electrical conductivity and the diatom indices in this study was not in agreement with the work of Stancheva et al. [26] who reported high negative correlation.

5. Conclusion

The diatom indices except the relative abundance of motile taxa were moderately correlated with physical and chemical parameters indicating their effectiveness in water quality ranking.

The water quality of the Ogun River during the study period as elucidated from the diatom indices ranged between bad and high qualities. Trophic diatom index (TDI) served as an indicator of silicates, biological diatom index (IBD) was an indicator of nitrites, generic salinity index (GSI1) was an indicator of nitrates and generic saprobity index (GSI2) was an indicator of iron, ammonium and total hardness. It can be concluded that trophic diatom index, biological diatom index, generic salinity index and generic saprobity index can be utilized in water quality assessment.

Limitations on the use of diatom indices in Nigeria include insufficient information on the autecology of diatom species in Nigeria. It is therefore recommended that the ecology of diatoms in Nigeria should be studied in detail in order to provide information on taxonomy, nomenclature, autecology, sensitivities and tolerance levels of diatoms to pollution in

Nigerian waters. Also, diatom keys, identification guides and diatom-based indices specific to water bodies in Nigeria should be developed just as is done in other regions of the world.

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Conflict of interest

The authors declare no conflicts of interest.

Author details

Adewole Michael Gbadebo[1], Benjamin Onozeyi Dimowo[1]*, Adewale Matthew Taiwo[1] and Isaac Tunde Omoniyi[2]

*Address all correspondence to: benjamindimowo@yahoo.com

1 Department of Environmental Management and Toxicology, Federal University of Agriculture, Abeokuta, Nigeria

2 Department of Aquaculture and Fisheries Management, Federal University of Agriculture, Abeokuta, Nigeria

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