Biodiversity and Conservation (2006) 15:3267–3293
DOI 10.1007/s10531-005-0600-3

Distribution of epilithic diatoms in response to environmental conditions in an urban tropical stream, Central Kenya

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Received 2 June 2004; accepted in revised form 20 June 2005

Key words: Biodiversity, Epilithic diatoms, Monitoring, Substrates, Trophic indices, Tropical stream, Water quality

Abstract. Use of diatoms in monitoring water quality is well acknowledged in developed countries, but only recently has the assessment started gaining importance in developing countries. Diatoms can be obtained from natural and artificial substrates. Appreciating the differences and similarities of diatom assemblages on both substrates may contribute to a better understanding and standardization particularly during monitoring of water quality. During this study we assessed diatom assemblages, biodiversity and trophic indices in relation to water quality along the Nairobi River. Fifteen sites were sampled in September 2000 during the dry season. Diatoms were collected from natural substrates (stones, pebbles) and artificial substrates (100% acrylic wool). On artificial and natural substrates, a total of 190 and 151 taxa were found, respectively, the majority of these taxa (80%) have cosmopolitan distribution and are also widespread throughout tropical African. Species composition changed downstream, five taxa dominated upper and mid stream sites whereas lower stream sites were dominated by one or two taxa. Species richness, diversity, dominance and evenness were positively correlated with NO_3, O_2 and altitude but decreased markedly downstream with a simultaneous increase in total dissolved solids, alkalinity, chemical oxygen demand and PO_4. Ordination and classification (CANOCO and TWINSPAN) showed that diatom assemblages in the Nairobi River responded strongly to water quality changes with respect to concentrations of NO_3, NO_2, total dissolved solids and temperature. Taxa common at less impacted upstream sites included *Gomphonema gracilis*, *Anomoeoneis brachysira* and *Fragilaria biceps*; while common taxa at midstream sites with agricultural catchments were *Gomphonema parvulum*, *Navicula cryptocephala*, *N. schroeteri*, *N. bryophila*, *N. halophila*, *Nitzschia linearis* var. *linearis* and *Cymbella silesica*. *Achnanthes minutissima* var. *saprophila*, *Gomphonema angustum*, *Navicula subminuscula*, *N. arvensis*, *Nitzschia palea* and *N. umbonata* were most common at urban sites, which were polluted by residential and industrial effluents. Trophic diatom indices suggested that water quality was poor at most sites in the Nairobi River. Most sites along the river had low Generic Diatom Index values, GDI ($<$12) and high Trophic Diatom Index values, TDI 73–78 (median = 76) and 75–84 (median = 77) for artificial and natural substrates, respectively. This study showed that diatoms' response on natural and artificial substrates were similar and reflected environmental conditions correctly.

Introduction

Lotic systems (i.e. rivers and streams) flowing through pristine landscapes present continuous gradient of physical, chemical and biological conditions that are predictable (Vannote et al. 1980). But conversion of landscapes into other uses such as agriculture, urban and industrial developments (towns) has altered environmental conditions in rivers with negative effects on their biotic components (Ometo et al. 2000; Jüttner et al. 2003; Ndaruga et al. 2004). Agricultural activities increase inputs of nutrients and sediments (Harding et al. 1999; Leland and Porter 2000), residential and commercial estates contribute large quantities of organic wastewater and solids (Lobo et al. 1995), while industries are sources of inorganic and thermal pollution (Izsak et al. 2002). Although information on the impacts of anthropogenic activities in lotic systems is well documented in developed countries (e.g. Rott 1991; EU 2000), very little is known from most developing countries, yet such data are important to develop appropriate management practices in riparian river basins (Fabricius et al. 2003).

Diatoms have been used successfully as good indicators to monitor environmental change (Stoermer and Smol 1999) and assess ecological integrity of lotic systems (Whitton and Rott 1996; Kelly 2000). Assessment of environmental conditions can be based on single species (Raschke 1993), a group of indicator species (Schoeman 1976; Ndiritu et al. 2003) or whole assemblages (Stevenson 1984; Jüttner et al. 1996). Using whole assemblages, several indices were derived to infer environmental conditions of habitats based on the autecology of diatoms (Stevenson and Pan 1999). Biodiversity indices (e.g. species richness, diversity, evenness) and autecology indices (e.g. TDI, Trophic Diatom Index; GDI, Generic Diatom Index) have been used to monitor environmental conditions of aquatic ecosystems with good results (e.g. Köster and Hübener 2001; Jüttner et al. 2003). However, responses of biotic indices to environmental conditions are not always predictable. Diversity can decrease with pollution (Rott and Pfister 1988), increase with pollution (van Dam 1982; Izsak et al. 2002), or changes can vary depending on the type of pollution (Jüttner et al. 1996; Hillebrand and Sommer 2000; Jüttner et al. 2003). Patrick (1973) hypothesized ambiguity in diversity assessment of pollution when using composite diversity because of differing effects of pollutants on species richness and evenness.

Periphyton assemblages for assessing water quality can be obtained from either natural or artificial substrates depending on the study objectives (Kelly et al. 1998). Artificial substrates can be used if suitable natural substrates are not available. However, there is evidence that natural and artificial substrates support different periphyton communities. Some researchers have found higher number of species on artificial than natural surfaces (Snoeijis 1991; Cronk and Mitsch 1994), but Dural et al. (1997) found more species on natural than artificial substrates. Lowe and Gale (1980) found that periphyton was comparable on both substrates. One major problem with periphyton assemblages on natural substrates is that they can be highly variable whilst those on artificial substrates vary less and are more sensitive to physical and chemical conditions in the water (Stevenson and Pan 1999). Cattaneo and Amireault (1992) recommended use of artificial substrates when monitoring of water quality is a priority rather than assessing the effects of water quality on a periphyton assemblage in a particular habitat.

In this paper, we describe the distribution pattern of epilithic diatom assemblages on natural and artificial substrates in an urban river and investigate whether they were related with environmental conditions along the Nairobi River. Our objectives were to (1) describe diatom assemblage and composition along a downstream section of the river; (2) determine whether biodiversity indices correlated with water quality; (3) select indicator species for monitoring water quality; and (4) assess whether the trophic indices TDI and GDI reflected pollution levels in Nairobi River.

Study area

The Nairobi River is an urban tropical river situated in Central Kenya (Figure 1). The section of the river studied (60 km) lies between an altitude of 2028 and 1503 metres above sea level (m a.s.l.) and has a drainage basin of 1350 km^2. The basin has a tropical climate, with temperatures between 14 and 28 °C. The wet season occurs during the months of March–May and October–December (Waters and Odero 1986). The Nairobi River is a first to third order stream, with mean discharge ranging from 0.03 to 0.2 and 2.72 m^3 s^{-1} in the upper, mid and lower sections, respectively, (Ndiritu et al. 2003). The river basin includes the Nairobi province and surrounding areas and receives water from five tributaries (Masongo, Ngong, Mathare, Ruaraka and Gatharaini), the Dandora water treatment plant and many discharges from broken water and sewer pipes. The river drains into the Athi River, the second largest river in Kenya.

Land use in the Nairobi River basin has changed due to the expansion of agriculture and urbanization since the early 1900s when the first European settlers arrived in Kenya and established Nairobi City as a center before continuing their journey to the White Highlands (UNEP 2001). The increase in human population from 0.7 m in 1975 to 2 m in 1999 has resulted in the reduction of pristine land and a significant production of waste (HABITAT 2002). Inappropriate waste disposal and environmental protection have resulted in serious environmental degradation in the river basin (UNEP 2001).

This study did not determine the exact area of each land use type in the Nairobi River basin, but dominant land use types and anthropogenic activities in the vicinity of each site were observed and recorded during data collection. The upper river section included areas east of Nairobi City (i.e. foot of Aberdare Ranges and southwest parts of Kiambu District), where settlements and mixed farming were the major forms of land use. The mid section of the river was

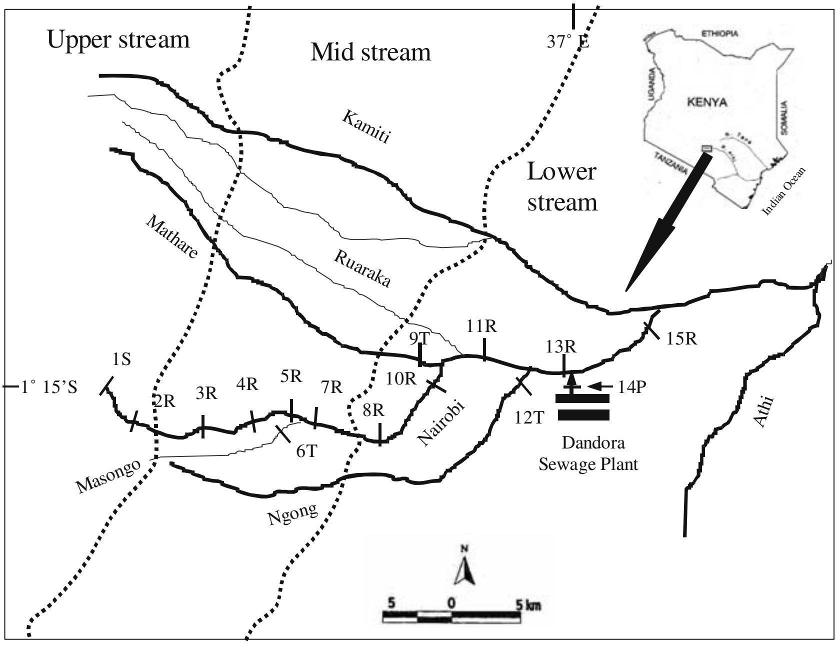

Figure 1. Inset: Map of Kenya showing location of Nairobi River and sampling sites. Letters on sites numbers S, R, T and P identify location of sampling points S, swamp; R, main river; T, tributary; P, sewage treatment plant. Dotted lines show the three major sections in the basin. Sections are not sketched to scale.

located in Dagoretti, Lang'ata, and southern areas of the Kiambu District. It was dominated by intensive mixed farming, planned and unplanned residential areas. The lower river section included the city center and eastern parts of the city of Embakasi, the Kahawa and Kasarani areas. The major forms of land use were commercial, industrial and residential developments.

Methods

Sampling strategy and laboratory procedures

The survey was conducted during the dry month of September 2000 when the river discharge was low and dilution particularly from rainwater was at its lowest levels. Fifteen sampling sites were selected at equidistance along the Nairobi River taking into account the levels of discharge, accessibility and results from previous studies (Kinyua and Pacini 1991; UNEP 2001). Three sites at the major tributaries (Masongo, Mathare and Ngong) were also investigated to establish their influence on the main river. Samples for water quality determination were taken twice, when placing and collecting the artificial substrates. Natural substrates were collected during retrieval of artificial substrates.

Water parameters determined in the field were pH (pH meter, Model 6301 Rabenau-Londorf, Germany), temperature, conductivity and total dissolved solids (TDS/Temperature meter, Hanna Model 4075, Jenway, Essex, UK). Dissolved oxygen was determined using the Winkler method (APHA 1995). Flow was measured (SEBA-Universal Current Meter F1, London, UK) and river discharge (in m^3s^{-1}) calculated (Jeffries and Mills 1990). For the determination of nutrients, turbidity, total suspended solids and chemical oxygen demand, water samples were collected in acid rinsed 150 ml plastic bottles and transported on ice cooled (<4 °C). In the laboratory samples were stored below 4 °C and analysed within 24 h. Spectrophotometric methods were used to determine dissolved inorganic nutrients, orthophosphate (PO_4): phosphorous-molybdate complex method, nitrate and nitrite: cadmium reduction and diazoic complex (Wood et al. 1967), and silicates: heteropoli blue, (APHA 1995). Alkalinity and water hardness were determined using back titration and ethylene diamine tetracetic acid titrimetrie, (APHA 1995). A Photometric method was used to measure total suspended solids (DR/2000 spectrophotometer, Hach 1996). An open reflux method was used to determine chemical oxygen demand (APHA 1995).

Epilithic diatoms were collected from natural and artificial substrates avoiding shaded sites and selecting locations with similar current speed (Kelly et al. 1998). For natural substrates submerged hard surfaces of stones and solids (approximately 100 cm^2), at locations of moderate flow were preferred. Diatoms were qualitatively collected from stone surfaces using a toothbrush and distilled water. The sample was preserved by adding 1 ml of 4% formalin. Prior to sampling epilithic surfaces, all substrates were either shaken in the stream or washed with water ejected from a washing bottle to remove any loosely attached sediments and non-epilithic diatoms. Diatoms from artificial substrates were collected from wool string (100% acrylic), 10 cm long and 6 mm wide, tied on an aluminium ring (θ 4 cm). The rings were tied to a pole and left suspended in the littoral parts of the river for 14 days prior to sampling.

Diatom frustules were cleaned with concentrated sulphuric and nitric acid (Hendey 1974). Diatom frustules from artificial substrates were obtained by digesting strings with acid. The acid-cleaned samples were suspended in water and mounted on slides with Styrax mounting medium. Two slides were prepared per sampling site, one deposited at the National Museums of Kenya and the other in the Laboratory of Plant Science and Nature Management, Vrije Universiteit Brussels, Belgium. Diatom valves were identified using a Leitz Dialux 20 EB light microscope at 1000× magnification and broken valves were only considered if more than half the size of the valve was intact. Three hundred diatom valves were counted along several transects. Diatoms were identified to species, and where possible to variety level. Taxonomic identifications followed Germain (1981), Gasse (1986), Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Sims et al. (1996) and Kelly (2000).

Diversity and statistical analysis

Species density was used to calculate relative abundance while species richness, diversity, dominance and evenness were calculated using several indices (Hill 1973; Pielou 1975):

pi = percentage (relative abundance) of species per site (assemblage);
$N_0 = \sum pi^0$ = total number of species present;
$N_1 = \exp [-\sum p_i \ln(p_i)] = \exp(H')$ = exponential Shannon-Wiener index;
$N_2 = (\sum p_i^2)^{-1}$ = reciprocal of Simpson's index;
$N_{INF} = (p_i)^{-1}$ = for the commonest species; and
$J' = \ln (N_1)/\ln (N_0)$

Diatom-based pollution indices (TDI, Kelly 2000; GDI, Rumeau and Coste 1988) were calculated and used to assess water quality at the sites. TDI has a scale from 0 to 100, with higher values indicating progressively higher levels of nutrients (Whitton and Kelly 1995). The interpretation of the TDI also requires the calculation of the percentage pollution tolerant valves (% PTV). Percentages PTV of more than 20% indicate that factors other than nutrients probably influence the diatom assemblages. GDI scores range from 4 to 20, with low values (<10) indicating heavy pollution and values (>16) indicating no or minimal pollution. Spearman rank correlation was performed to investigate relationships between environmental conditions and biodiversity indices. Analysis of variance (ANOVA, Tukey HSD for unequal N) was done to test whether environmental variables and biodiversity indices changed significantly downstream. All parametric analyses were performed using STATISTICA (StatSoft Inc. 1996). All data were log-transformed prior to analyses to meet the statistical criteria of normality.

To investigate assemblage composition in relation to environmental variables Canonical Correspondence Analysis, CCA, ter Braak and Smilauer (1999) and Two Way Indicator Species Analysis, TWINSPAN, McCune and Mefford (1999) were performed. During CCA, Monte Carlo permutations were done so as to identify a subset of measured environmental variables, which exerted significant and independent influences on diatom distribution at $p < 0.05$ (ter Braak and Smilauer 1999). To define site groups with similar diatom assemblages and indicator species, TWINSPAN classification was performed using the same species data as in CCA. For CCA and TWINSPAN rare diatom species which occurred at less than 1% in one or more sites were excluded.

Results

Characterization of stream sites

Use of environmental and diatom data in multivariate analysis of CCA and TWINSPAN suggested three groups of sites (Figures 4 and 5). One cluster purely consisted of upper stream sites (1S, 2R), the second cluster primarily contained mid stream sites (3R, 4R, 5R, 6T, 7R) and the third cluster included lower stream sites (8R, 9T, 10R, 12T, 13R, 14P, 15R). There was some overlapping of mid and lower stream sites. Medians and interquartile ranges of environmental variables showed a consistent increase or decrease in variable values from upstream to downstream sites (Table 1). Oxygen concentration decreased significantly from 8.2 mg l^{-1} in the upper stream section to 0.2 mg l^{-1} downstream (ANOVA, $p < 0.01$). Temperature ranged from 19.3 to 21.4 °C and was only significantly different between mid-stream and lower stream sites (ANOVA, $p < 0.001$). Similarly, alkalinity varied significantly between all groups, rising from 47 mg l^{-1} in upper stream to 206 mg l^{-1} in lower stream (ANOVA, $p < 0.001$).

Total dissolved solids increased from 463 mg l^{-1} (upper stream) to 1367 mg l^{-1} (lower stream) and chemical oxygen demand ranged from 30 to 178 mg l^{-1}. Differences between upstream and downstream sites were significant for both variables (ANOVA, $p < 0.01$). Total suspended solids and water hardness increased from 25 and 64 mg l^{-1} to 656 and 107 mg l^{-1}, respectively. However, the increases were not significant among the three grouped sites (ANOVA, $p < 0.05$). Nitrate concentration increased significantly from upper to mid stream sites (139–3804 μg l^{-1}) but decreased significantly at downstream sites (ANOVA, $p < 0.01$). There was no significant difference between the upper and lower stream section. Orthophosphate and altitude differed markedly between the three groups (ANOVA, $p < 0.001$). At mid and lower stream sites pH was not significantly different, but both were significantly different to pH at upper stream sites (ANOVA, $p < 0.05$). There was no significant difference in NO_2 and SiO_4 concentrations between the three groups of sites ($p < 0.05$). Variables indicating pollutions such as alkalinity, total dissolved solids, total suspended solids, total dissolved solids, COD and PO_4 were negatively correlated with O_2 and temperature. However, their correlation with NO_3 and NO_2 were weak (Table 2).

Diatom community structure

A total of 190 and 151 diatom taxa were found on artificial and natural substrates, respectively. The majority were cosmopolitan (80%) but tropical African taxa were also recorded. Assemblage composition differed between sites and between artificial and natural substrates (Figure 2). On the artificial substrate five most characteristic species at upstream sites 1S and 2R

Table 1. Comparison of environmental variables, presented as median, 1st and 3rd interquartile ranges for the three groups of sites as suggested in CCA and TWINSPAN.

Attributes	Abbreviations	Site groups		
		Upper stream (n = 4)	Mid stream (n = 10)	Lower stream (n = 14)
Altitude (m)	ALT	2026.1 (2024.9–2027.2)^{a}	1693.1 (1693.1–1761.1)^{b}	1550.6 (1523.9–1629.7)^{c}
pH (units)	PH	5.8 (5.6–6.1)^{a}	7.4 (7.2–7.5)^{b}	7.7 (7.4–7.8)^{b}
Disolved oxygen (mg l^{-1})	O_2	8.2 (8.0–8.3)^{a}	2.6 (2.2–3.9)^{b}	0.16 (0.16–0.32)^{c}
Temperature (O °C)	TEMP	19.3 (19.2–19.4)^{a}	19.0 (18.8–19.2)^{a}	21.4 (20.6–22.2)^{a,b}
Alkalinity (mg l^{-1})	ALK	46.5 (45.3–47.8)^{a}	78.0 (73.0–84.0)^{b}	206.0 (184.0–239.5)^{c}
Hardness (mg l^{-1})	HRD	64.0 (57.5–70.5)^{a}	99.0 (98.0–99.0)^{a}	106.5 (91.0–126.3)^{a}
Total dissolved solids (mg l^{-1})	TDS	463.3 (455.4–471.1)^{a}	966.0 (939.7–994.5)^{b}	1367.3 (1285.3–1522.4)^{c}
Conductivity (μS cm^{-1})	COND	668 (648.3–688)^{a}	1440 (1416.7–1441.7)^{b}	2003.3 (1898.8–2243.3)^{c}
Total suspended solids (mg l^{-1})	TSS	24.5 (21.6–27.4)^{a}	67.3 (66.0–98.0)^{a}	655.7 (286.2–891.8)^{a}
Turbidity (NTU)	TURB	1.45 (1.2–1.69)^{a}	2.63 (2.57–2.87)^{b}	15.18 (7.37–18.09)^{c}
Discharge (m^3 s^{-1})	DSC	0.02 (0.01–0.03)^{a}	0.25 (0.15–0.26)^{b}	0.56 (0.51–1.94)^{c}
Chemical oxygen demand (O mg l^{-1})	COD	30.4 (20–40.8)^{a}	64.0 (32–67.2)^{b}	177.6 (130.4–206.4)^{c}
Nitrate μg l^{-1}	NO_3	139.0 (116.5–161.5)^{a}	3804.4 (3577.1–4077.1)^{b}	192.7 (160.2–435.2)^{c}
Nitrite (μg l^{-1})	NO_2	46 (33.5–58.5)^{a}	1017.0 (794.3–1037.5)^{a}	158.5 (56.0–463.5)^{a}
Phosphate (μg l^{-1})	PO_4	7.9 (7.2–8.3)^{a}	166.7 (140.0–166.7)^{b}	3660.4 (2822.6–4120.8)^{c}
Silicate (mg l^{-1})	SiO_4	26.8 (26.6 –27.0)^{a}	24.1 (19.8–25.1)^{a}	18.3 (17.8–19.2)^{a}

Superscript letters (^{a,b,c}) indicate significant differences among the groups according to post hoc tests. Only classes not sharing a letter differed from each other significantly at $p < 0.05$.

Table 2. Spearman's rank correlation coefficients between biodiversity indices, diatom-based pollution indices and environmental variables.

	N_O_A	N_1_A	N_{INF}_A	J′_A	TDI_A	GDI_A	N_O_N	N_1N	N_{INF}_N	J′_N	TDI_N	GDI_N	ALT	PH	O_2	TEMP	ALK	TDS	TSS	TURB	DSC	COD	NO_3
N_1_A	0.8																						
N_{INF}A	0.6	0.9																					
J′_A	0.6	0.9	0.9																				
TDI_A	0.5	0.2	0.1	0.1																			
GDI_A	0.6	0.6	0.6	0.7	−0.1																		
N_O_N	0.8	0.8	0.8	0.8	0.2	0.7																	
N_1_N	0.6	0.5	0.6	0.6	0.1	0.7	0.9																
N_{INF}_N	0.4	0.3	0.4	0.4	0.0	0.7	0.7	0.9															
J′_N	0.3	0.3	0.5	0.4	0.0	0.6	0.7	0.9	0.9														
TDI_N	0.0	−0.4	−0.5	−0.5	0.6	−0.4	−0.2	−0.2	0.0	−0.2													
GDI_N	−0.1	0.0	0.1	0.1	−0.2	0.1	0.2	0.2	0.4	0.3	0.1												
ALT	0.7	0.7	0.6	0.7	0.0	1.0	0.7	0.7	0.7	0.6	−0.4	0.1											
PH	−0.4	−0.4	−0.3	−0.4	−0.1	−0.6	−0.2	−0.2	−0.3	−0.2	0.1	−0.1	−0.7										
O_2	0.5	0.4	0.4	0.3	−0.2	0.8	0.6	0.6	0.7	0.5	−0.1	0.5	0.8	−0.5									
TEMP	−0.6	−0.4	−0.5	−0.4	0.0	−0.7	−0.7	−0.7	−0.7	−0.6	0.2	0.0	−0.6	0.2	−0.6								
ALK	−0.6	−0.6	−0.5	−0.6	−0.1	−0.9	−0.5	−0.4	−0.4	−0.3	0.2	−0.2	−0.8	0.8	−0.7	0.4							
TDS	−0.6	−0.7	−0.7	−0.7	0.1	−0.9	−0.7	−0.6	−0.6	−0.5	0.3	−0.2	−0.9	0.7	−0.8	0.6	0.9						
TSS	−0.2	−0.2	−0.3	−0.2	0.2	−0.4	−0.5	−0.6	−0.7	−0.6	0.0	−0.6	−0.5	0.2	−0.7	0.5	0.3	0.4					
TURB	−0.2	−0.2	−0.3	−0.2	0.1	−0.5	−0.5	−0.6	−0.8	−0.7	−0.1	−0.6	−0.5	0.2	−0.8	0.6	0.3	0.5	1.0				
DSC	−0.5	−0.6	−0.6	−0.6	0.1	−0.8	−0.7	−0.7	−0.8	−0.6	0.2	−0.3	−0.9	0.5	−0.8	0.6	0.6	0.8	0.8	0.8			
COD	−0.4	−0.3	−0.4	−0.3	0.3	−0.6	−0.6	−0.7	−0.7	−0.6	0.1	−0.5	−0.7	0.3	−0.9	0.7	0.5	0.7	0.9	0.9	0.8		
NO_3	0.6	0.4	0.3	0.3	0.6	0.2	0.6	0.5	0.4	0.4	0.5	0.4	0.2	0.0	0.3	−0.4	−0.2	−0.2	−0.3	−0.4	−0.3	−0.3	
NO_2	0.3	−0.1	−0.1	−0.2	0.7	−0.1	0.2	0.2	0.3	0.2	0.8	0.1	−0.1	0.1	0.1	−0.1	0.0	0.1	−0.3	−0.4	−0.2	−0.2	0.7
PO_4	−0.6	−0.5	−0.5	−0.5	0.2	−0.9	−0.6	−0.7	−0.7	−0.6	0.3	−0.3	−0.9	0.6	−0.8	0.8	0.7	0.8	0.5	0.6	0.7	0.8	−0.2

Biodiversity indices (N_0, species richness; N_1, species diversity; N_{INF}, species dominance; J′, species evenness); diatom-based pollution indices (TDI, Trophic Diatom Index; GDI, Generic Diatom Index). At the end of each acronym is Letters A and N for artificial and natural substrates. ALT, altitude; TEMP, temperature; ALK, alkalinity; TDS, total dissolved solids; TSS, total dissolved solids; TURB, turbidity; DSC, discharge. Correlation values (r) = 0.5, 0.6 and >0.7 indicate significant levels at p = 0.05, 0.01 and 0.001, respectively.

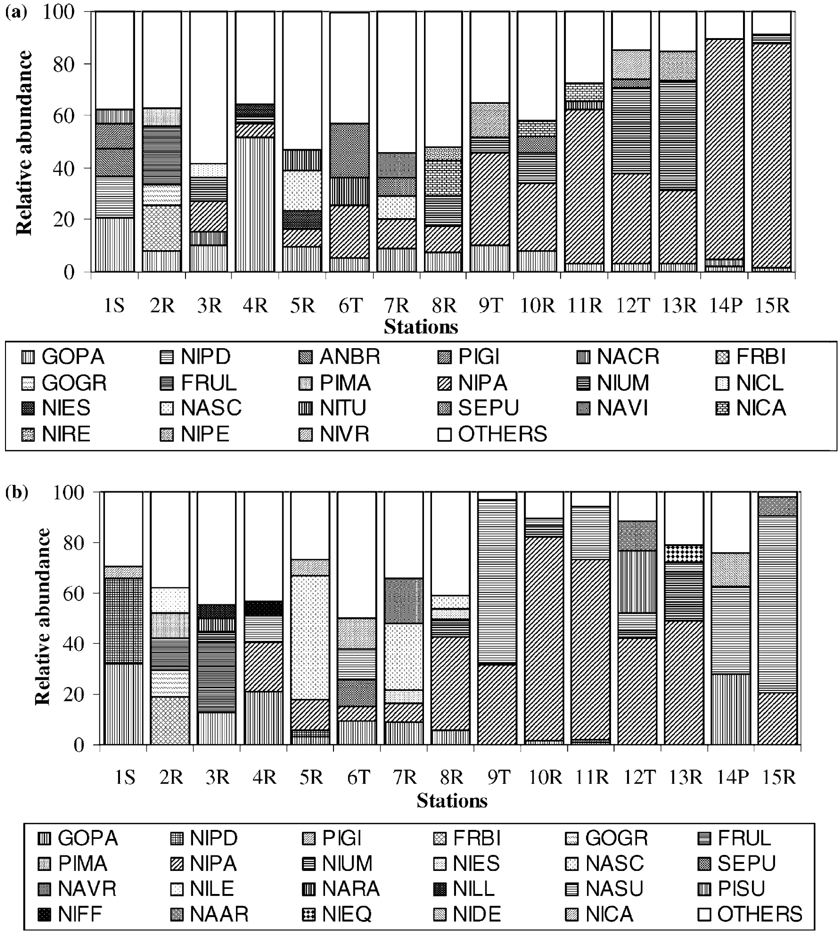

Figure 2. Diatom taxonomic composition on artificial (a) and natural (b) substrates. Letters on sites numbers S, R, T and P identify location of sampling points (i.e. (S) swamp, (R) main river, (T) tributary and (P) sewage treatment plant. Species codes and full species names are ANBR, *Anomoeoneis brachysira* (Brébisson) Grunow; DIEL, *Diploneis elliptica* (Kützing) Cleve; FRBI, *Fragilaria biceps* (Kützing) Lange-Bertalot; FRUL, *F. ulna* (Nitzsch) Lange-Bertalot; GOGR, *Gomphonema gracile* Ehrenberg; GOPA, *G. parvulum* (Kützing) Kützing; NAAR, *Navicula arvensis* Hustedt; NACR, *N. cryptocephala* Kützing; NARA, *N. radiosa* Kützing; NASC, *N. schroeterii* Meister; NASU, *N. subminuscula* Manguin; NAVR, *N. viridula* var. *rostellata* (Kützing) Cleve.; NICA, *Nitzschia capitellata* Hustedt; NICL, *N. clausii* Hantzsch; NIDE, *N. desertorum* Hustedt; NIES, *N. estohensis* Cholnoky; NIFF, *N. frustulum* var. *frustulum* (Kützing) Grunow; NILL, *N. linearis* var. *linearis* (Agardh) W. Smith; NIPD, *N. palea* var. *debilis* (Kützing) Grunow; NIPA, *N. palea (Kützing) W. Smith*; NIPE, *N. perminuta* (Grunow) M. Peragallo; NIRE, *N. recta* Hantzsch; NITU, *N. tubicola* Grunow; NIUM, *N. umbonata* (Ehrenberg) Lange-Bertalot; PIGI, *Pinnularia gibba* Ehrenberg; PIMA, *P. maior* (Kützing) Rabenhorst; PISU, *P. subcapitata* Gregory; SEPU, *Sellaphora pupula* Kützing (Mereschkowsky).

represented 61% of all the species, while, only one or two species were dominant at downstream sites 4R, 9T, 10R, 11R, 12T, 13R, 14P and 15R. *Gomphonema parvulum* occurred in all sites and was dominant in site 4R while *Nitzschia palea* was frequent and dominant at sites 6T, 9T, 10R, 11R, 12T, 13R, 14P and 15R. Other common species included *Nitzschia umbonata* (3R, 8R, 10R, 12T and 13R), *Sellaphora pupula* (6T, 7R, 10R and 12T), *Nitzschia perminuta* (9T and 13R), *Navicula schroeteri* (5R and 7R), *Fragilaria biceps* (2R) and *Nitzschia palea* var. *debilis* (1S).

On the natural substrate *Nitzschia palea* was the most conspicuous at sites 8R, 9T, 10R, 11R, 12T and 13R while *Navicula subminuscula* was common at sites 6T, 10R, 11R, 12T, 13R and was dominant in sites 9T, 14P and 15R. *Gomphonema parvulum* was frequent at sites 1S, 3R, 4R, 5R, 6T, 7R, 8R, 10R, 11R, 14P, while *Gomphonema gracilis* was only common at site 2R. *Navicula schroeteri* was dominant at sites 5R and 7R. *Nitzschia umbonata*, *N. palea* var. *debilis*, *Pinnularia subcapitata* and *Navicula viridula* var. *rostellata* were common at sites 1S, 13R, 12T and 7R, respectively. Large species such as *Fragilaria ulna* was abundant at sites 2R and 3R while *Fragilaria biceps* was only common at site 2R.

Biodiversity indices

Biodiversity indices showed marked decrease in species richness (N_0), diversity (N_1, N_2), dominance (N_{INF}) and evenness (J') from sites 11R to 15R (Figure 3). Comparison of biodiversity indices on artificial substrates using ANOVA showed significant differences between mid- and lower stream sites in species richness ($p < 0.007$) and diversity ($p < 0.05$). Similarly, for assemblages on natural substrate, species richness ($p < 0.001$), diversity ($p < 0.007$) and dominances ($p < 0.02$) significantly decreased from mid- to lower stream. Further analysis (*t*-test) showed that species richness ($p < 0.001$) and diversity ($p < 0.02$) were significantly higher on artificial than natural substrates, though species dominance and evenness were similar. Species richness and diversity on both substrates were significantly correlated at ($p < 0.05$, Table 2). Biodiversity indices were significantly negatively correlated with total dissolved solids, alkalinity, chemical oxygen demand and PO_4, but were positively correlated with NO_3, O_2 and altitude.

Gradient analysis

Sixty-three and 50 diatom taxa from artificial and natural substrates, respectively, with abundance of more than 1% were used in CCA and TWINSPAN analyses. For artificial substrates the first and second CCA axes explained 18.9 and 16.9%, of the species variance while for natural substrates they explained 27.2 and 15% (Figure 4, Table 3). Unrestricted Monte

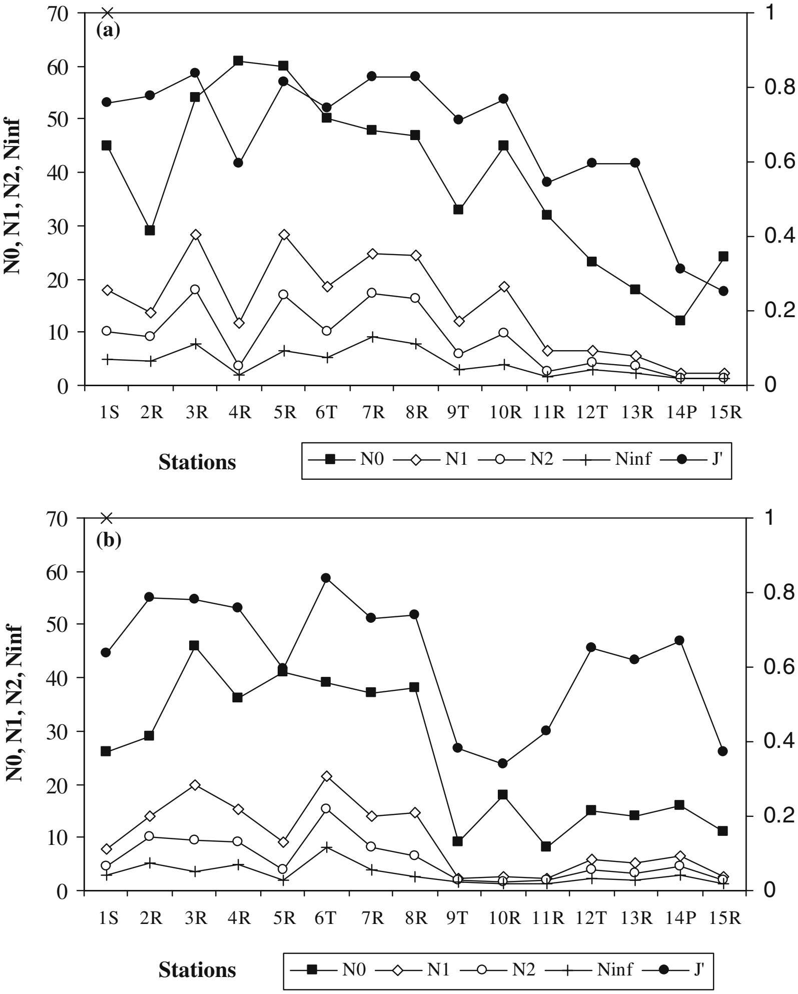

Figure 3. Diatom species indices (N_0 – species richness, N_1 and N_2 – species diversity, N_{INF} – species dominance, J' – species evenness) in artificial (a) and natural (b) substrates. Letters on sites numbers S, R, T and P identify location of sampling points (i.e. (S) swamp, (R) main river, (T) tributary and (P) sewage treatment plant.

Carlo permutation tests and randomization indicated that altitude, temperature, NO_3 and NO_2 were significantly correlated with diatoms on artificial substrate whereas, total dissolved solids, NO_3 and NO_2 were significantly correlated with diatom assemblages on natural substrates (p = 0.05, Table 3). Other variables with strong correlations with diatom assemblages included conductivity and PO_4 (in artificial substrates) and discharge, O_2, PO_4, conductivity, alkalinity and COD (in natural substrates). The CCA diatom triplots for natural and artificial substrates showed three groups of

Table 3. A CCA species-environment weighted correlation matrix and conditional effects (F and p values) after Monte Carlo permutations for artificial and natural substrates. Significant level were accepted at $p < 0.05$ (*).

	Species environment axes			Conditional effects	
	Axis 1	Axis 2	Axis 3	F	p levels
Artificial substrates					
Altitude	0.71	−0.66	−0.66	2.68	0.01*
pH	−0.64	0.48	0.40	1.41	0.14
O_2	0.74	−0.53	0.10	1.29	0.27
Temperature	−0.12	0.57	−0.65	1.76	0.03*
Water hardness	−0.34	0.47	0.34	0.99	0.52
Alkalinity	−0.38	0.78	0.05	0.99	0.47
TDS	−0.52	0.83	0.08	1.11	0.38
Conductivity	−0.50	0.83	0.14	1.27	0.40
TSS	−0.21	0.41	−0.40	1.00	1.00
Turbidity	−0.27	0.36	−0.45	0.00	1.00
Discharge	−0.14	0.62	0.09	1.43	0.17
COD	−0.26	0.51	−0.48	0.00	1.00
NO_3	−0.45	−0.55	0.28	2.18	0.02*
NO_2	−0.40	−0.08	−0.04	1.77	0.04*
PO_4	−0.19	0.77	−0.44	0.99	0.44
SiO_4	0.43	−0.47	−0.07	1.49	0.38
Natural substrates					
Altitude	−0.77	0.38	0.38	0.00	1.00
pH	0.44	−0.36	0.23	0.94	0.43
O_2	−0.66	0.41	−0.12	1.24	0.37
Temperature	0.68	0.14	−0.04	1.29	0.25
Water hardness	0.59	−0.11	0.34	1.09	0.35
Alkalinity	0.82	0.04	0.07	1.24	0.31
TDS	0.85	−0.20	0.18	3.62	0.01*
Conductivity	0.83	−0.20	0.14	1.07	0.43
TSS	0.39	−0.29	−0.45	0.00	1.00
Turbidity	0.33	−0.28	−0.51	1.63	0.06
Discharge	0.65	−0.25	−0.26	1.35	0.27
COD	0.58	−0.25	−0.32	1.52	0.13
NO_3	−0.50	−0.30	0.64	2.15	0.01*
NO_2	0.05	0.14	0.77	2.46	0.01*
PO_4	0.83	0.15	−0.02	1.30	0.40
SiO_4	−0.56	0.36	0.32	0.00	1.00

▶

Figure 4. CCA triplot of artificial (a) and natural (b) substrates for species, sites and environmental variables. Variables that significantly related with diatoms (at $p < 0.05$) were altitude, temperature, NO_3, NO_2 (on artificial substrates) and TDS, NO_3, and NO_2 (on natural substrates). Dotted circles represent the three suggested site groups with different environmental conditions in Nairobi River. Note that some species abbreviations are hidden. Species code and full name are given in Table 4.

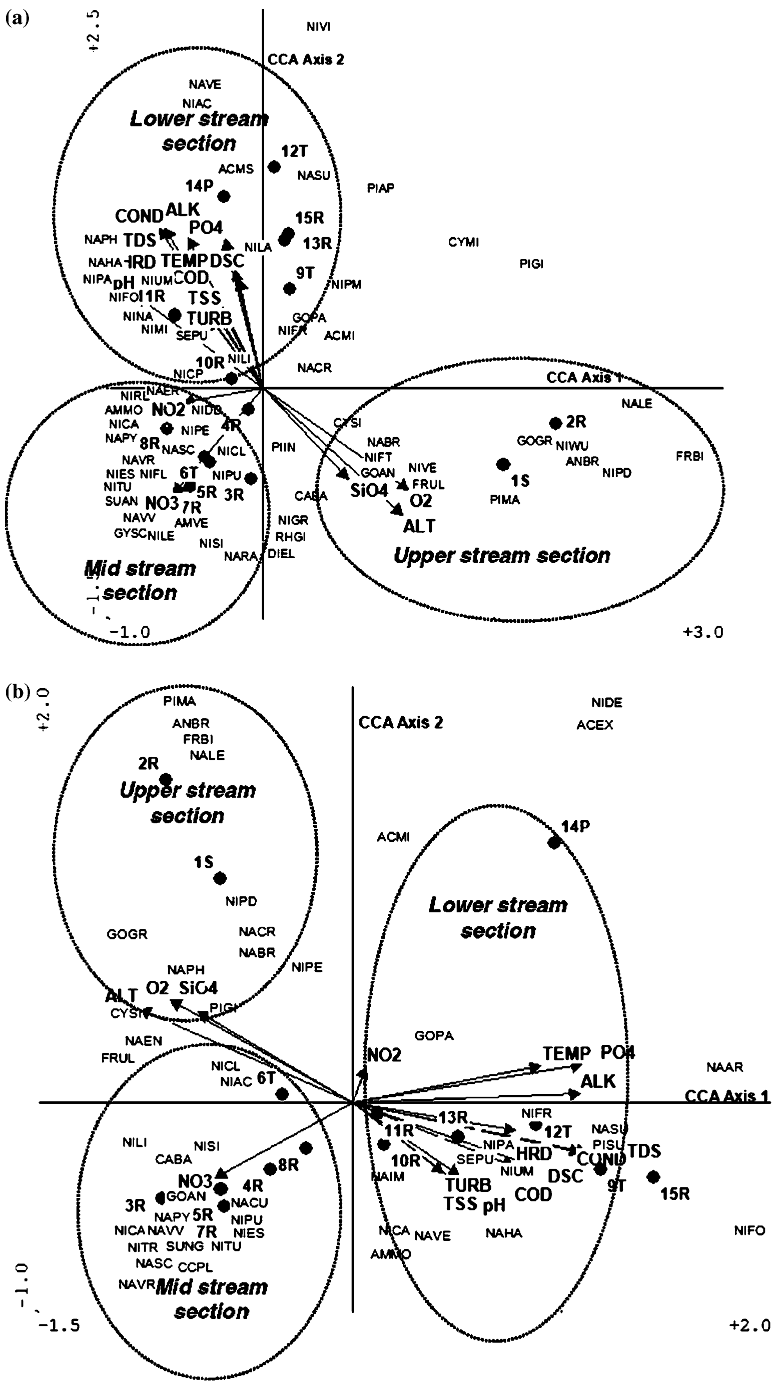
(a)
+2.5
CCA Axis 2
CCA Axis 1
Lower stream section
Mid stream section
Upper stream section
12T
14P
15R
13R
9T
11R
10R
8R
4R
6T
5R
7R
3R
2R
1S
COND
ALK
PO4
TDS
HRD
TEMP
DSC
pH
COD
TSS
TURB
NO2
NO3
SiO4
O2
ALT
NIVI
NAVE
NIAC
ACMS
NASU
PIAP
CYMI
PIGI
NAPH
NAHA
NIPA
NIFO
NINA
NIMI
NIUM
SEPU
NILA
NIPM
GOPA
ACMI
NACR
NILI
NICP
NIRI
NAER
AMMO
NIDD
NICA
NIPE
NAPY
NASC
NICL
NAVR
NIES
NIFL
NIPU
NITU
SUAN
NAVV
AMVE
GYSC
NILE
NISI
NARA
DIEL
RHGI
NIGR
CABA
PIIN
CYSI
NABR
NIFT
GOAN
NIVE
FRUL
GOGR
NIWU
ANBR
NIPD
NALE
FRBI
PIMA
-1.0
+3.0
(b)
+2.0
CCA Axis 2
CCA Axis 1
Upper stream section
Lower stream section
Mid stream section
PIMA
ANBR
FRBI
NALE
2R
1S
NIPD
GOGR
NACR
NABR
NIPE
NAPH
ALT
O2
SiO4
CYSI
PIGI
NAEN
FRUL
NICL
NIAC
6T
NIDE
ACEX
ACMI
14P
GOPA
NO2
TEMP
PO4
ALK
NAAR
13R
NIFR
12T
NASU
PISU
TDS
11R
NIPA
HRD
COND
10R
SEPU
NIUM
DSC
9T
15R
NAIM
TURB
TSS
pH
COD
NICA
NAVE
NAHA
NIFO
AMMO
NILI
NISI
CABA
NO3
8R
4R
3R
GOAN
NACU
NAPY
5R
NIPU
NICA
NAVV
7R
NIES
NITR
SUNG
NITU
NASC
CCPL
NAVR
-1.0
-1.5
+2.0

Table 4. Diatom species full names and codes as used in Figure 4.

Code	Species name	A	N	Code	Species name	A	N
ACEX	*Achnanthes exigua* Grunow		**	NICP	*N. capitellata* Hustedt	**	**
ACMI	*Achnanthes minutissima* Kützing	**	**	NICL	*N. clausii* Hantzsch	**	**
ACMS	*A. minutissima* var. *saprophila* (Kobayasi and Mayama)	**	–	NIDE	*N. desertorum* Hustedt	–	**
AMMO	*Amphora montana* Krasske	**	**	NIDD	*N. dissipata* var. dissipata (Kützing) Grunow	**	*
AMVE	*A. veneta* Kützing	**	–	NIDM	*N. dissipata* var. *media* (Hantzsch) Grunow	**	*
ANBR	*Anomoeoneis brachysira* (Brébisson) Grunow	**	**	NIES	*N. estohensis* Cholnoky	**	**
CABA	*Caloneis bacillum* (Grunow) Cleve	**	**	NIFL	*N. flexoides* Gitler	**	*
CCPL	*Cocconeis placentula* var. *lineata* (Ehrenberg) Van Heurck	*	**	NIFO	*N. fonticola* Grunow	**	**
CYMI	*Cymbella minuta* Hilse	**	*	NIFR	*N. frustulum* var. *frustulum* (Kützing) Grunow	**	**
CYSI	*C. silesiaca* Bleisch	**	**	NIFT	*N. fruticosa* Hustedt	**	*
DIEL	*Diploneis elliptica* (Kützing) Cleve	**	–	NIGR	*N. gracilis* Hantzsch	**	*
FRBI	*Fragilaria biceps* (Kützing) Lange-Bertalot	**	**	NILA	*N. latens* Hustedt	**	–
FRUL	*F. ulna* (Nitzsch) Lange-Bertalot	**	**	NILE	*N. levidensis* (W. Smith) Grunow var. *levidensis*	**	–
FRVU	*F. vulgaris* (Thwaites) De Toni	*	**	NILI	*N. linearis* var. *linearis* (Agardh) W. Smith	**	**
GOAN	*Gomphonema angustum* Agardh	**	**	NIMI	*N. microcephala* Grunow	**	–
GOGR	*G. gracile* Ehrenberg	**	**	NINA	*N. nana* Grunow	**	*
GOPA	*G. parvulum* (Kützing) Kützing	**	**	NIPA	*N. paleaeformis* Hustedt	**	*
GYSC	*Gyrosigma scalproides* (Rabenhorst) Cleve	**	*	NIPD	*N. palea* var. *debilis* (Kützing) Grunow	**	**
NAAR	*Navicula arvensis* Hustedt	–	**	NIPA	*N. palea* (Kützing) W. Smith	**	**
NABR	*N. bryophila* Petersen	**	**	NIPE	*N. perminuta* (Grunow) M. Peragallo	**	**

NACR	*N. cryptocephala* Kützing	**	**	NIPU	*N. pusilla* Grunow	**	**
NACU	*N. cuspidata* Kützing	*	**	NIRE	*N. recta* Hantzsch	**	*
NAEN	*N. enigmatica* Germain	–	**	NISI	*N. sigmoidea* (Nitzsch) W. Smith	**	**
NAER	*N. erifuga* Lange-Bertalot	**	–	NITR	*N. tryblionella* Hantzsch	*	**
NAHA	*N. halophila* (Grunow) Cleve	**	**	NITU	*N. tubicola* Grunow	**	**
NAIM	*N. impexa* Hustedt	*	**	NIUM	*N. umbonata* (Ehrenberg) Lange-Bertalot	**	**
NALE	*N. leptostriata* Jørgensen	**	**	NIVE	*N. vermicularis* (Kützing) Hantzsch	**	*
NAPH	*N. phyllepta* Kützing	**	**	NIVI	*N. vitrea* var. *vitrea* Norman	**	*
NAPY	*N. pygmaea* Kützing	**	**	NIWU	*N. wuellerstorffii* Lange-Bertalot	**	–
NARA	*N. radiosa* Kützing	**	**	PIAP	*P. appendiculata* (Agardh) Cleve	**	–
NASC	*N. schroeterii* Meister	**	**	PIGI	*P. gibba* Ehrenberg	**	**
NASU	*N. subminuscula* Manguin	**	**	PIIN	*P. interrupta* W. Smith	**	*
NAVE	*N. veneta* Kützing	**	**	PIMA	*P. maior* (Kützing) Rabenhorst	**	**
NAVV	*N. viridula* var. *viridula* (Kützing) Ehrenberg	**	**	PISU	*P. subcapitata* Gregory	*	**
NAVR	*N. viridula* var. *rostellata* (Kützing) Cleve	**	**	RHGI	*Rhopalodia gibberula* (Her.) O. Mull.	**	–
NIAC	*Nitzschia acidoclinata* Lange-Bertalot	**	**	SEPU	*Sellaphora pupula* (Kützing) Mereschkowsky	**	**
NICA	*N. calida* Grunow	**	**	SUAN	*Surirella angusta* Kützing	**	**

A and N are diatoms on artificial and natural substrates, respectively; (**), taxa present in more than one site and abundance was more than 1%; (*), taxa abundance was less than 1% and not used in CCA and TWINSPAN analysis; (–), taxa was not present in all sites.

sites and species which had significant correlations with different environmental variables. For artificial substrates, species tended to cluster at the centre of ordination diagram whereas species from natural substrates diagram showed spreading and clustering around sites they were common (Figure 4).

A careful look at the CCA diagram indicated that diatoms assemblages responded to three environmental gradients in Nairobi River. The first group comprised upper stream sites 1S and 2R and was positively correlated with altitude and oxygen concentration but negatively with pH and TDS. Diatom species associated with upper river section included *Anomoeoneis brachysira*, *Cymbella minuta*, *Fragilaria biceps*, *F. ulna*, *Gomphonema gracile*, *Navicula bryophila*, *N. leptostriata*, *N. phyllepta*, *N. leptostriata*, *N. cryptocephala*, *N. halophila*, *Nitzschia dissipata* var. *media*, *N. palea* var. *debilis*, *N. vermicularis*, *Pinnularia gibba* and *P. maior*. The second group contained sites in the midstream section which had higher concentrations of NO_3 for both artificial and natural substrates. Although NO_3 was positively correlated with NO_2 for artificial substrates both were not correlated with other variables. Species common in the mid river sections were *Cocconeis placentula* var. *lineata*, *Cymbella silesiaca*, *Gomphonema parvulum*, *Navicula erifuga*, *N. radiosa*, *N. viridula* var. *rostellata*, *N. schroeterii*, *N. viridula* var. *viridula*, *Nitzschia calida*, *N. capitellata*, *N. frustulum*, *N. estohensis*, *N. linearis* var. *linearis*, *N. tryblionella*, *N. tubicola* and *Surirella angusta*. The third group comprised sites in the lower river section and diatom assemblages were significantly influenced by pollution indicating variables of TDS, conductivity, PO_4, COD, and temperature (for artificial substrate) and TDS, alkalinity, discharge, PO_4, NO_2 and COD (for natural substrate). Characteristics species of downstream sections included *Achnanthes exigua*, *A. minutissima*, *Gomphonema angustum*, *Navicula arvensis*, *N. subminuscula*, *N. veneta*, *Nitzschia acidoclinata*, *N. desertorum*, *N. aequorea*, *N. fonticola*, *N. recta*, *N. perminuta*, *N. palea*, *N. vitrea* var. *vitrea*, *N. umbonata*, *Pinnularia appendiculata* and *P. subcapitata*.

TWINSPAN classification separated sites and gave indicator species for the three different environmental conditions in the upper-, mid- and lower sections of the Nairobi River. In figure 5, species on the right hand side were positively while those on left were negatively associated with those sites grouped on the right hand side of the dendrogram. On artificial substrate, *Fragilaria biceps* was associated with the upper stream section; *Surirella angusta* and *Navicula halophila* were characteristic species for mid stream sites; and *Achnanthes minutissima* var. *saprophila* was an indicator species for lower sites. *Gomphonema parvulum*, *Cymbella silesiaca* and *Nitzschia linearis* var. *linearis* separated upper- and mid- from lower stream sites for natural substrate. *Achnanthes exigua*, *Gomphonema angustatum* and *Navicula arvensis* were associated with lower stream sites while *Anomoeoneis brachysira* characterised upper stream and *Navicula cryptocephala* and *Navicula bryophila* were indicators species for mid stream sites.

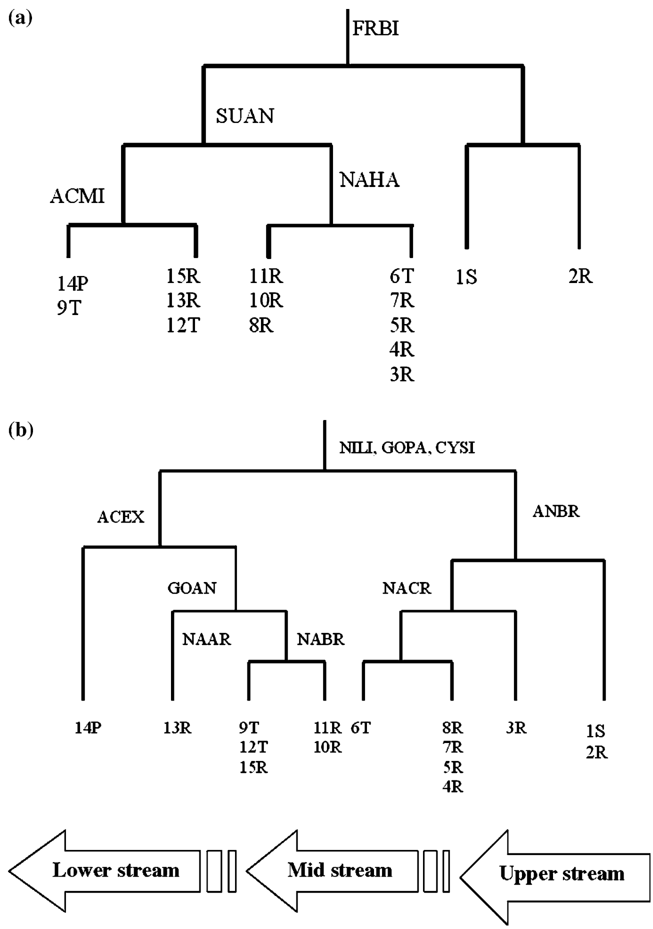

Figure 5. Dendrogram showing the TWINSPAN classification of sites based on diatom species percentages: (a) artificial substrates and (b) natural substrates. Note the clustering of sites into upper-, mid- and lower stream section in both substrates as in CCA (see Figure 1 for explanation). Water quality was observed to deteriorate downstream. Full species names can be found in Table 4.

Water quality assessment

The Trophic Diatom Index (TDI) was high at all sites for both substrates except at site 2R (47 and 50 on artificial and natural substrate, respectively). They ranged from 73 to 78 (median = 76) on artificial and 75 to 84 (median = 77) on natural substrate (Figure 6). Values for TDI increased significantly downstream. TDI values at upper stream sites were significantly different when compared to mid- (p = 0.003) and lower (p = 0.001) stream sites on artificial substrate. However, there was no marked change between mid- and lower stream sites. In contrast, on natural substrate, TDI values did

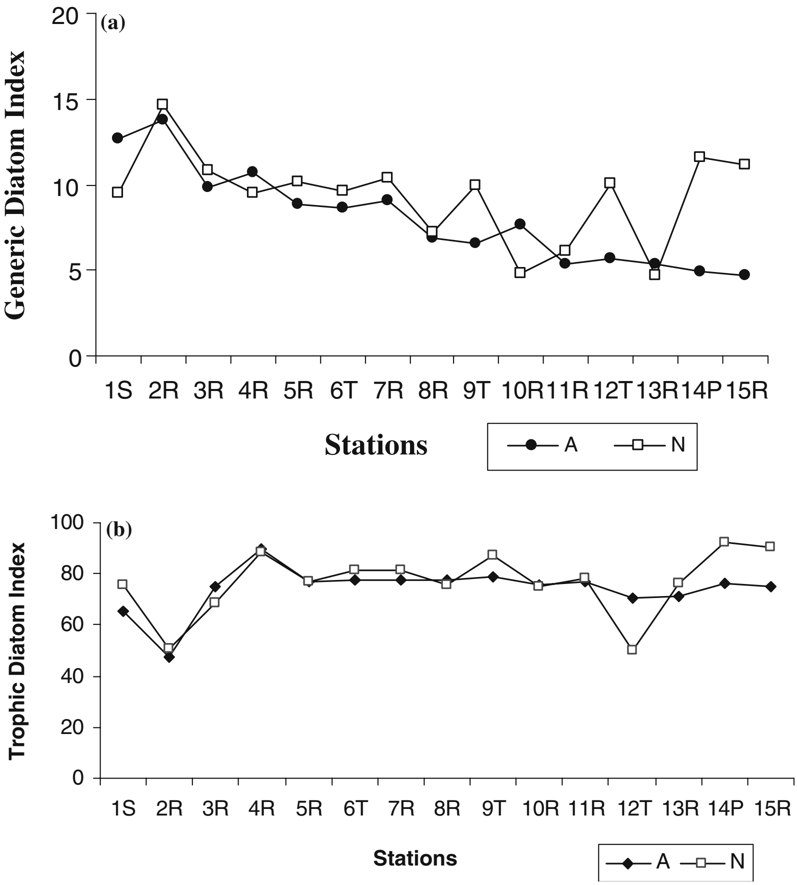

Figure 6. Generic Diatom Index, GDI (a) and Trophic Diatom index, TDI (b). Letters (A) and (N) in the legend refers to artificial and natural substrates, respectively. Letters on station numbers S, R, T and P identify location of sampling points S, swamp; R, main river; T, tributary; P, sewage treatment plant. Note that GDI values less than 15 and TDI values of more than 50% indicates different levels of severe pollution.

not change significantly between upper, mid- and lower stream sites. Percentage Pollution Tolerant Values (PTV) ranged from 6 to 19 (median = 14) and 12 to 47 (median = 25) on artificial and natural substrates, respectively. High percentage of pollution tolerant species were recorded at sites 1S, 4R, 6T, 9T, 11R, 12T, 14P, 15R for natural and 1S, 4R, 6T for artificial substrates (Figure 6).

Values for the Generic Diatom Index (GDI) decreased from 14 to 5 (median = 8) for assemblages on artificial substrate and were significantly different between upper, mid- and lower stream sites ($p < 0.001$, Figure 7). But GDI values for assemblages on natural substrate did not change downstream and

UK TDI	Percent of taxa tolerant to organic pollution (%)							
	1-10	11-20	21-30	31-40	41-50	51-60	61-70	>71
40-49		**2R_A**						
50-59	***2R_N***		***12T_N***					
60-69		***3R_N***	**IS_A**					
70-79	**11R_A, 12T_A, 13R_A, 14P_A, 15R_A,** ***5R_N, 10R_N, 13R_N***	**3R_A, 5R_A, 7R_A, 8R_A, 9T_A, 10R_A,** ***8R_N***	**6T_A,** ***11R_N***	***1S_N***				
80-89		***7R_N***			***6T_N, 4R_N***		***9T_N***	
≥90						**4R_A**	***14P_N***	***15R_N***

Figure 7. The U.K. Trophic Diatom Index and percentage of pollution tolerant taxa determined for Nairobi River on artificial (regular) and natural (italic) substrates. Most sites had more than 50% TDI values an indication of serious pollution. Percent of taxa tolerant to organic pollution were higher in natural substrates than in artificial substrates.

varied between 8 and 11 (median = 10) without significant differences between the three site groups. There was strong correlation ($r > 0.6$, $p = 0.01$) between GDI and biodiversity indices (N_0, N_1, N_{INF}, J') on artificial substrate (Table 3). While, TDI values for assemblages on artificial substrate were less strongly correlated with N_0 ($r = 0.5$, $p = 0.05$). Consistently, GDI values for assemblages on artificial substrate were significantly negatively correlated with water quality parameters (NO_3, NO_2, pH, temperature, alkalinity, total dissolved solids, discharge and PO_4, ($p = 0.001$, Table 2), whereas TDI values were only correlated with NO_3 ($r = -0.6$, $p = 0.01$) and NO_2 ($r = -0.7$, $p = 0.001$). Equally, TDI values for assemblages on natural substrate were significantly correlated with NO_3 ($r = -0.5$, $p = 0.05$) and NO_2 ($r = -0.8$, $p = 0.001$) whilst GDI values were positively correlated with O_2 ($r = 0.5$, $p = 0.05$), and negatively with total suspended solids ($r = -0.6$, $p = 0.01$).

Discussion

Describing riverine landscape and its relation to biodiversity patterns and disturbances, Ward (1998) observed that the river channels are part of an extensive interconnected series of biotopes and environmental gradients that together with their biotic communities constitute lotic ecosystems. Jeffries and Mills (1990) reported that marked perturbation and alterations in the catchments can be reflected by changes in the rivers further downstream. During this study water quality and diatom assemblages changed significantly downstream the Nairobi River probably due to land use changes in the catchment. The upper stream sites formed a distinct group that was associated with moderate mixed farming and small scale human settlements. The overlapping mid and lower stream sites' groups were situated in catchments with intensive agriculture densely populated residential and industrial areas. Overlapping of sites was attributed to transitional nature from upper to lower stream.

High species richness and diversity at mid river sites supports the intermediate disturbance hypothesis (IDH) which states that diversity peaks at an intermediate frequency or intensity of disturbance as result of the co-existence of pioneers, stress-tolerants and ruderals species (Connell 1978). Low biodiversity indices (N_0, N_1, N_2, N_{inf}, J') observed at downstream sites resembled results by Hillebrand and Sommer (2000), who found that artificial eutrophication led to a decrease in diversity of benthic microalgae. As species diversity decreased, assemblages were dominated by only a few species (i.e. reduced evenness). Ilka Schönfelder et al. (2001) observed that high littoral diatom species diversity was evident in rivers with high total nitrogen and total nitrogen and in mesotropic sites. Biggs 1996, Lobo et al. (1995) and Jüttner et al. (2003) suggested that maximum periphyton diversity was typical for low to intermediate levels of disturbance and nutrient supply. They also stated that heavily polluted waters supported diatom assemblages with low diversity and richness but high cell densities. During this study, high species diversity was recorded at upper to mid stream sections. Those areas experienced intermediate impacts from agriculture activities and small scale human settlement. Downstream sites had low biodiversity indices and were subject to high levels of disturbances due to pollution from domestic, agricultural and industrial sources.

Decrease in biodiversity and changes in species composition downstream were related to changes in water quality and increasing pollution. Stevenson (1997) noted that communities can adapt to environmental stress by changing species composition. During this study the heavily impacted lower stream sites mostly supported small to medium sized species such as*Navicula subminuscula*, *Nitzschia desertorum*, *N. palea*, and *Pinnularia subcapitata*, while less disturbed upper stream sites supported medium to large sized species such as *Fragilaria biceps*, *F. ulna*, *Nitzschia sigmoidea* and *Pinnularia maior*. Brackish water species such as *Nitzschia umbonata* were also present at lower stream sites whereas the medium sized *Navicula schroeteri* was frequent at mid stream sites. *Gomphonema parvulum* abundance decreased downstream while *Nitzschia palea* increased markedly as water quality deteriorated.

Canonical correspondence analyses showed that diatom assemblages at upper stream sites were strongly influenced by altitude and oxygen (on artificial substrates), assemblages at midstream sites by NO_3 and NO_2 (on both substrates) and assemblages at downstream sites by temperature, conductivity, PO_4, (on artificial substrates) and alkalinity, COD, conductivity, total dissolved solids, discharge and PO_4 (on natural substrates). Studies done elsewhere concurred with our predictions that water quality in stream sites situated in agricultural areas are characterized by high NO_3, NO_2 and total suspended solids (Leland and Porter 2000) whilst those in residential and industrial areas have elevated levels of total dissolved solids, PO_4, conductivity, total dissolved solids, alkalinity, COD and temperature (Lobo et al. 1995; Jüttner et al. 2003). Similarly, high PO_4 concentrations were observed to be closely related with the suspended solids from agricultural fields and sewage effluents (O'Farrell et al. 1996; McCormick and Stevenson 1998). The significant influence of altitude on diatoms assemblages on artificial substrates though at a local scale agreed with Potapova et al. (2002) findings in USA rivers that altitudinal variation of temperature was responsible for one-third of total explainable variation in distribution in benthic diatoms.

Analyses of CCA and TWINSPAN identified diatom taxa closely associated with the three site groups characterized by different environmental conditions and were comparable to other findings (Aboal et al. 1996; Lobo et al. 1995; Leland and Porter 2000; Fabricius et al. 2003). Results from our study showed that diatom species associated with less impacted stream sites included *Anomoeoneis brachysira*, *Cymbella minuta*, *Fragilaria biceps*, *F. ulna*, *Gomphonema gracile*, *Navicula bryophila*, *N. leptostriata*, *N. phyllepta*, *N. leptostriata*, *N. cryptocephala*, *N. halophila*, *Nitzschia dissipata* var. *media*, *N. palea* var. *debilis*, *N. vermicularis*, *Pinnularia gibba* and *P. maior*. Characteristic diatom species for moderately agriculturally impacted sites with higher concentrations of NO_3 were *Cocconeis placentula* var. *lineata*, *Cymbella silesiaca*, *Gomphonema parvulum*, *Navicula erifuga*, *N. radiosa*, *N. viridula* var. *rostellata*, *N. schroeterii*, *N. viridula* var. *viridula*, *Nitzschia calida*, *N. capitellata*, *N. frustulum*, *N. estohensis*, *N. linearis* var. *linearis*, *N. tryblionella*, *N. tubicola* and *Surirella angusta*. Heavily impacted downstream sites with elevated levels of pollution indicating variables (such as TDS, conductivity, PO_4, COD, temperature, TDS, alkalinity, discharge and COD) were characterized by *Achnanthes exigua*, *A. minutissima*, *Gomphonema angustum*, *Navicula arvensis*, *N. subminuscula*, *N. veneta*, *Nitzschia acidoclinata*, *N. desertorum*, *N. aequorea*, *N. fonticola*, *N. recta*, *N. perminuta*, *N. palea*, *N. vitrea* var. *vitrea*, *N. umbonata*, *Pinnularia appendiculata* and *P. subcapitata*. Lobo et al. (1995) in a Tokyo Metropolitan area found that *Achnanthes minutissima* var. *saprophila*, *Navicula subminuscula* dominated heavily polluted sites; *Gomphonema parvulum* and *Navicula cryptocephala* were typical for moderately impacted sites; and *Cymbella minuta* was common at less impacted stream sites. Similarly, Aboal et al. (1996) noted that *Achnanthes minutissima* was resistant to heavy and frequent discharges. Our findings were in consistent with Leland and Porter (2000) that prostrate diatoms, notably *Nitzschia frustulum*, *Gomphonema parvulum*, *Nitzschia dissipata*, *N. fonticola* and *N. palea* were abundant in rivers draining agricultural areas that had high phosphates and nitrate levels. Equally, Fabricius et al. (2003) found that *Navicula subminuscula*, *Sellaphora pupula*, *Nitzschia palea* and *N. umbonata* were associated with high conductivity and higher nutrient concentrations (e.g. NO_3) whilst streams in urban areas were characterized by *Nitzschia palea* and stream in catchments with low agricultural intensity by *G. parvulum* and *Achnanthes minutissima*. A keen look at the diatom distribution indicated a number of species were common in three sites groups experiencing different environmental conditions (e.g. *G. parvulum A. minutissima*, *Nitzschia perminuta*, *N. palea* and *Navicula subminuscula*). van Dam et al. (1994) and Köster and Hübener (2001) reported that *G. parvulum* has wide ecological ranges and tolerates considerable organic pollution whereas *A. minutissima*, *Nitzschia perminuta*, *N. palea* and *Navicula subminuscula* have been found to tolerate different pollution levels from different sources (e.g. agricultural, residential and industrial areas).

Results from our study agreed with those of Köster and Hübener (2001) and Jüttner et al. (2003) that trophic indices can indicate tropic status of streams. High TDI and low GDI values at most sites confirmed that rivers in Nairobi City and its surroundings were negatively impacted by changes in land use to intensive agriculture, residential and industrial areas. Trophic indices from both substrates gave reliable results, with GDI from artificial substrates showing significant correlation with biodiversity indices, suggesting that diatom assemblages on artificial substrate reflected environmental conditions more accurately than those on natural substrates. Percentage pollution tolerant species were higher in natural than artificial substrates an indication that natural substrates contained more pollution tolerant species than artificial substrates. Somehow diatom assemblages on natural and artificial substrates and derived indices differed due to several reasons. Higher diversity and evenness observed for assemblages on artificial substrate might be due to less mature assemblages present at the beginning of colonization processes when several species appear simultaneously in about the same number (Acs and Kiss 1991). As periphyton communities mature they are strongly influenced by endogenous processes and there is a tendency for better competitors to proliferate and dominate (Lowe et al. 1996; Hillebrand and Sommer 2000). Another possibility is that stones had more dead diatom valves, which had accumulated overtime and they would not reflect environmental conditions at the time of sampling. The use of artificial substrates has been recommended when monitoring water quality is a priority rather than assessing the effects of water quality on a periphyton assemblage in a particular habitat (Catteneo and Amireault 1992). Jüttner et al. (2003) and Köster and Hübener (2001) noted that some indices could not accurately reflect water quality because the response of particular taxa to water chemistry might vary between geographical regions, or taxa indicating different ecological conditions are being combined under a single name. Nevertheless, the use of TDI and GDI indices offer a good compromise between the exact estimation of trophic parameters and the need to simplify the practical (especially the taxonomic) work.

Our results supported findings from other studies that diatoms are suitable indicators for changes in environmental conditions such as increase in nutrients (NO_3, NO_2, PO_4), total dissolved solids, total suspended solids, alkalinity, COD and temperature. Biodiversity indices (i.e. richness and diversity), assemblage composition and trophic indices (TDI, GDI) reflected changes in water quality due to anthropogenic impacts and land use change in the river catchment. Although diatom assemblages on both artificial and natural substrates were comparable, trophic indices of diatom assemblages on artificial substrates reflected environmental conditions more accurately than diatom assemblages on natural substrates. It was clear, however, that more research is needed in the tropics to determine the true optima and tolerance levels of most diatoms and facilitate the use of trophic indices in these least studied waters. Such information will be vital for understanding the consequences of human population growth and urbanizations in lotic systems (e.g. eutrophication and saprobication) and how it can be mitigated particularly in less developed countries where environmental monitoring is seldomly done.

Acknowledgements

This research work was part of a post-graduate degree study sponsored by the Belgium Government through Flemish Interuniversity Council (VLIR). National Museums of Kenya (Wetland Biology Laboratory) supported the fieldwork. We thank Jane M. Macharia, Taita Terer, Stephen Mathaai and Ayub Macharia of National Museums of Kenya for fieldwork assistance. Henry Lung'ayia of Kenya Marine and Fisheries Research Institute, J.J. Symoens and Parminder Kaur of Plant Science and Nature Management Laboratory, Vrije Universiteit Brussel, Belgium for their help in diatoms identification. We are also grateful to the anonymous reviewers who made valuable suggestions on our original manuscript.

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