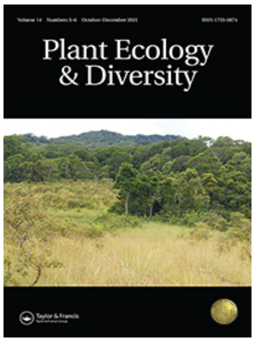

Taylor & Francis
Taylor & Francis Group

Plant Ecology & Diversity

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tped20

Epipelic diatom diversity as a bioindicator in River Aturukuku, Eastern Uganda

Hannington Ochieng, Godfrey Magezi, Willy P. Gandhi, James Okot-Okumu & Robinson Odong

To cite this article: Hannington Ochieng, Godfrey Magezi, Willy P. Gandhi, James Okot-Okumu & Robinson Odong (2022): Epipelic diatom diversity as a bioindicator in River Aturukuku, Eastern Uganda, Plant Ecology & Diversity, DOI: 10.1080/17550874.2022.2058430

To link to this article: https://doi.org/10.1080/17550874.2022.2058430

PLANT ECOLOGY & DIVERSITY
https://doi.org/10.1080/17550874.2022.2058430

Taylor & Francis
Taylor & Francis Group

Epipelic diatom diversity as a bioindicator in River Aturukuku, Eastern Uganda

Hannington Ochieng [a], Godfrey Magezi [b], Willy P. Gandhi [b], James Okot-Okumu [c] and Robinson Odong [d]

[a]Department of Biology, Faculty of Science and Education, Busitema University, Tororo, Uganda; [b]Fish Habitat Management Program, National Fisheries Resources Research Institute, National Agricultural Research Organisation, Jinja, Uganda; [c]Consultant Environment and Natural Resources, Kampala, Uganda; [d]Department of Zoology, Entomology and Fisheries Sciences, College of Natural Sciences, Makerere University, Kampala, Uganda

ABSTRACT

Background: Despite their key ecological functions and application in biomonitoring, little is known about the algal flora in Uganda, especially those of lotic systems.
Aim: This study related the community composition of the epipelic diatoms to environmental variables to establish the influence of rural and urban activities on water quality and on the biota on spatial and seasonal scales along River Aturukuku in Eastern Uganda.
Methods: Epipelic diatoms and selected environmental variables were compared among sites: two urban, a reference site upstream, and a site downstream from the urban area, spanning the dry and wet seasons from February to October, 2018.
Results: Total phosphorus and nitrogen concentrations were above the natural threshold in the river. The diatom species such as *Gyrosigma attenuatum* and *Placoneis gastrum*, tolerant of pollution, dominated in the river. Total phosphorus, pH, temperature, and bottom substrates were most related to the composition of the diatom communities. The abundances of *P. gastrum* and *Sellaphora nyassensis* correlated with increased pH at the urban sewage effluent, suggesting that they are potential indicators of this kind of polluted environment.
Conclusions:: The study provides baseline information on diatom community, and is relevant for biomonitoring and biodiversity conservation in Uganda and other tropical countries.

ARTICLE HISTORY
Received 16 March 2021
Accepted 23 March 2022

KEYWORDS
Biological integrity; catchment degradation; diatoms; ecological functions; species tolerance

Introduction

Diatoms are photosynthetic eukaryotic micro-organisms (Lund 1949; Crawford 1975; Round et al. 1990). They are the most ubiquitous group among the microscopic algae, inhabiting almost all types of aquatic habitats (Stevenson et al. 2010; Zimmermann et al. 2014). They are either free-living as plankton or attached to the benthic surfaces of both lotic and lentic ecosystems (Patrick 1977; Round 1981; Sabater 2009). Epipelic diatoms are those that are attached to sediments (e.g. mud, silt, and sand) (Stevenson et al. 1996; Çiçek and Ertan 2016). Freshwater diatoms have numerous key ecological functions. As primary producers, they contribute much to the production of oxygen, play important roles in nutrient cycling, energy flow, and supply of energy to higher trophic levels (Mann 1999; Poulíčková and Manoylov 2019). They are part of the first trophic level in the ecosystem pyramid and are involved in the production of organic matter using nitrogen and phosphorus compounds. The concentrations of these nutrients are related to both the abundance and species composition of diatom communities and thus forming a feedback loop in natural as well as anthropogenically impacted aquatic ecosystems (Kelly 1998; Barinova 2017).

Diatoms respond rapidly to environmental degradation and therefore their community structure provides a measure of river ecosystem health. As a result, especially in the developed countries, diatoms have gained importance for their use as alternatives to physico-chemical water quality assessment methods, which offer limited holistic interpretation of aquatic ecosystem health and integrity (Bere 2015; Park and Hwang 2016). Epipelic diatoms are of particular interest in the context of environmental bioindication because of their varying sensitivity and response to pollution. Their diversity and community composition adapt rapidly to the disturbance arising from chemical, physical, and biological factors (Stevenson and Smol 2003; Chonova et al. 2019). Diatoms have been used as bioindicators for different environmental disturbances related to acidification, nutrient loading, climate, water temperatures and hydrological alterations (Tornés et al. 2018; Soininen and Teittinen 2019), given their high

CONTACT Hannington Ochieng ochiengho@gmail.com
Supplemental data for this article can be accessed here

sensitivity (Tornés et al. 2018) and faster response than organisms such as macroinvertebrates and fish (Wang et al. 2014). Diatoms tend to react quickly to changes in water quality because of their short life cycle, which allows them to adapt rapidly to water physico-chemistry (Solak et al. 2020). The faster response and strong relation to physico-chemical variables make diatoms good bioindicators of eutrophication and point and non-point source impacts, and their occurrence in a wide variety of environments, including heavily polluted ecosystems, allows monitoring where other types of organisms are absent (Beyene et al. 2009).

Pollution impacts such as increased water conductivity and eutrophication (e.g. orthophosphate and nitrite-nitrogen), can lead to a decreased diversity and species richness, and overall dominance by pollution tolerant taxa of diatoms (Kivrak and Uygun 2012). Similarly, a significant relationship between nutrient (e.g. nitrogen and phosphorus) enrichment and increase in density, or decrease in species richness and diversity of diatoms, have been reported (Licursi et al. 2015) and proposed for indication of eutrophication in tropical streams (Wang et al. 2014). An association between a high concentration of total phosphorus and pollution tolerant diatom genera, such as *Gomphonema, Navicula* and *Nitzschia*, has been reported for river reaches impacted by organic pollution from sewage spillages in Zimbabwe (Nhiwatiwa et al. 2017). Likewise, Triest et al. (2012) have found that relatively clean waters of low organic loads, high dissolved oxygen, and low total dissolved solids had communities of pollution-sensitive diatom taxa (e.g. *Gomphonema angustum, Navicula exigua, N. schroeteri, Frustulia rhomboides, Staurosira subsalina*, and *Nitzschia perminuta*) within the upstream waters of some rivers in Kenya. Meanwhile, polluted waters of heavy organic loads, low dissolved oxygen and high trophic state had pollution-tolerant taxa (e.g. *Nitzschia palea, N. umbonata, Gomphonema parvulum*, and *Stephanodiscus rotula*) in the downstream waters of the same rivers (Triest et al. 2012).

Despite their key ecological functions and application in biomonitoring, little is known about the algal floral in Uganda, especially those within the lotic systems. Most previous work has concentrated on plankton groups within lentic systems (Okello et al. 2010; Haande et al. 2011; Nankabirwa et al. 2019) compared with benthic groups especially in lotic systems (Pentecost et al. 1997). Globally, lotic systems such as rivers are among the most diverse ecosystems, with numerous ecological and socio-economic contributions but they are also the most impacted by anthropogenic activities (Sabater and Elosegi 2014). Lotic systems have experienced high rates of decline in biodiversity because of loss of habitats and catchment degradation associated with human activities such as land conversion for agriculture, settlement, urban development, industrial establishments, dam construction and pollution (Munir et al. 2016; Dudgeon 2019). In particular, the lotic systems in many tropical countries (e.g. Uganda) suffer environmental degradation because of rapid growth of population, agricultural activities and urbanisation, and limited resources and infrastructure for advanced pollution controls (Kwok et al. 2007; Cantonati et al. 2020).

Benthic diatom communities are among the aquatic biota whose biodiversity is disturbed by changes in environmental conditions arising from human activities, including sewage and wastewater effluents (Bere and Mangadze 2014; Chonova et al. 2019), river channelisation, the establishment of embankments across natural flow direction and agricultural run-off (Amutha and Muralidharan 2017). In Uganda, human activities (e.g. industrialisation, urbanisation, hydropower generation, mining and agriculture) affect the catchments of most rivers (Kasangaki et al. 2008; Atwebembeire et al. 2019; Musonge et al. 2020), including River Aturukuku, the subject of this study, causing disturbance to their environment and biota. As human populations and exploitation of water resources such as rivers expand, increase in the deterioration of water quality and decline in biodiversity are anticipated (Dudgeon 2019). This calls for an urgent need for monitoring and assessment of river health and biota for effective freshwater ecosystem management (Bere 2015; Park and Hwang 2016).

Although some rivers and streams in Uganda have been ecologically assessed mainly by relating their macroinvertebrate metrics to the physico-chemical variables (e.g. Kasangaki et al. 2008; Atwebembeire et al. 2019; Musonge et al. 2020), such biological communities show a time lag to respond to changes in water quality (Leps et al. 2016; Atwebembeire et al. 2019) compared with the diatoms that display quick responses (Beyene et al. 2009). A diatom-based monitoring approach is particularly suitable for the management of rivers in Uganda and other developing countries, given the similarities in the physico-chemical and biological attributes and the environmental threats associated with these

Acknowledgements

The research was made possible by the early career financial grant (Number CP-135ER-17) from the National Geographic Society, Washington, D. C. Small equipment grants provided by IDEA WILD are highly appreciated. We are grateful to the Director of Research, at the National Fisheries Resources Research Institute (NaFIRRI), Jinja, who permitted us to use the institute's laboratories for sample analyses. We thank Mr. Henry Ocaya, from NaFIRRI, for assistance during the water sample analysis. The study area map was produced by Mr. Paul M. Gudoyi, a collaborating lecturer in the Department of Geography, Faculty of Science and Education, Busitema University. Mr. David Amwonya from Kyambogo University contributed to the multivariate data analysis. Our special thanks to the anonymous native English speaker, and the aquatic and marine ecologist, for proofreading the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Geographic Society, Washington, D. C. [Early career grant (Number CP-135ER-17)].

Notes on contributors

Hannington Ochieng is a Ph.D. student with an interest in freshwater ecosystem monitoring and conservation.

Godfrey Magezi is a laboratory technician with long-term experience in freshwater monitoring. His technical expertise is in the areas of algal sampling, analyses and taxonomy.

Willy P. Gandhi is a laboratory technician with long-term experience in freshwater monitoring. His technical expertise is in the areas of macroinvertebrate sampling, analyses and taxonomy.

James Okot-Okumu is a Professor of Environmental Science with over 30 years of professional experience in water resources management, waste management and sanitation, and environmental and social impact assessment.

Robinson Odong is a lecturer of invertebrate zoology. He is interested in limnological research, especially environmental bio-monitoring.

ORCID

Hannington Ochieng http://orcid.org/0000-0003-0192-2691
James Okot-Okumu http://orcid.org/0000-0001-9197-3833
Robinson Odong http://orcid.org/0000-0002-0391-7434

References

Amutha M, Muralidharan M. 2017. Diatom community structure along physicochemical gradients in upland river segments of tamiraparani river system, South India. Int J Aquat Biol. 5:12–21.

An SM, Choi DH, Lee JH, Lee H, Noh JH. 2017. Identification of benthic diatoms isolated from the eastern tidal flats of the yellow sea: comparison between morphological and molecular approaches. Plos One. 12 (6):e0179422. doi:10.1371/journal.pone.0179422.

APHA. 1999. Standard methods for the examination of water and wastewater. 20th edn. Washington (D. C): American Public Health Association.1268.

Atwebembeire J, Andama M, Bazira J, Lejju JB, Tumusiime J, Wangalwa R, Yatuha J. 2019. The biological integrity of streams and channels draining into the rwizi river system in western Uganda. East Afr J Sci Technol Innovation. 1(1):82–101. doi:10.37425/eajsti.v1i1.65.

Barinova S. 2017. Essential and practical bioindication methods and systems for the water quality assessment. Int J Environ Sci Nat Resour. 2(3):555588. doi:10.19080/IJESNR.2017.02.555588.

Bartozek ECR, Zorzal-Almeida S, Bicudo DC. 2018. Surface sediment and phytoplankton diatoms across a trophic gradient in tropical reservoirs: new records for Brazil and São Paulo State. Hoehnea. 45(1):69–92. doi:10.1590/2236-8906-51/2017.

Battarbee RW. 1986. Diatom Analysis. In: Berglund BE, editor. Handbook of Holocene Paleoecology and Paleohydrology. Chichester (Great Britain): John Wiley & Sons Ltd; p. 527–570.

Bellinger BJ, Cocquyt C, O'Reilly CM. 2006. Benthic diatoms as indicators of eutrophication in tropical streams. Hydrobiologia. 573(1):75–87. doi:10.1007/s10750-006-0262-5.

Bere T. 2010. Benthic diatom community structure and habitat preferences along an urban pollution gradient in the Monjolinho River, São Carlos, SP, Brazil. Acta Limnol Bras. 22(1):80–92. doi:10.4322/actalb.02201011.

Bere T. 2015. Challenges of diatom-based biological monitoring and assessment of streams in developing countries. Environ Sci Pollut Res. 23(6):5477–5486. doi:10.1007/s11356-015-5790-y.

Bere T, Mangadze T. 2014. Diatom communities in streams draining urban areas: community structure in relation to environmental variables. Trop Ecol. 55:271–281.

Bere T, Mangadze T, Mwedzi T. 2014. The application and testing of diatom-based indices of stream water quality in Chinhoyi Town, Zimbabwe. Water SA. 40(3):503. doi:10.4314/wsa.v40i3.14.

Bere T, Tundisi JG. 2011. Diatom-based water quality assessment in streams influence by urban pollution: effects of natural and two selected artificial substrates, Sao Carlos-SP, Brazil. Braz J Aquat Sci Technol. 15 (1):54–63. doi:10.14210/bjast.v15n1.p54-63.

Beyene A, Addis T, Kifle D, Legesse W, Kloos H, Triest L. 2009. Comparative study of diatoms and macroinvertebrates as indicators of severe water pollution: case study of the Kebena and Akaki rivers in Addis Ababa, Ethiopia. Ecol Indic. 9 (2):381–392. doi:10.1016/j.ecolind.2008.05.001.

Blackburn-Lynch WC, Agouridis CT, Sanderson TM. 2016. Measuring discharge in wadeable streams. Agric Nat Res Publ. 87:4.

Bojorge-García M, Carmona J, Ramírez R. 2014. Species richness and diversity of benthic diatom communities in tropical mountain streams of Mexico. Inland Waters. 4 (3):279–292. doi:10.5268/IW-4.3.568.

Buck D, Esselman P, Jiang S, Wainwright J, Brenner M, Cohen M. 2019. Seasonal fluxes of dissolved nutrients in streams of catchments dominated by swidden agriculture in the maya forest of belize, Central America. Water. 11 (4):664. doi:10.3390/w11040664.

Caires AM, Chandra S. 2012. Conversion factors as determined by relative macroinvertebrate sampling efficiencies of four common benthic grab samplers. J Freshwater Ecol. 27:97–109.

Cantonati M, Poikane S, Pringle CM, Stevens LE, Turak E, Heino J, Richardson JS, Bolpagni R, Borrini A, Cid N, et al. 2020. Characteristics, main impacts, and stewardship of natural and artificial freshwater environments: consequences for biodiversity conservation. Water. 12 (1):260. doi:10.3390/w12010260

Chapman LJ, Schneider KR, Apodaca C, Chapman CA. 2004. Respiratory ecology of macroinvertebrates in a Swamp-River system of East Africa. Biotropica. 36:572–585.

Chen X, Zhou W, Pickett STA, Li W, Han L, Ren Y. 2016. Diatoms are better indicators of urban stream conditions: a case study in Beijing, China. Ecol Indic. 60:265–274. doi:10.1016/j.ecolind.2015.06.039.

Chonova T, Kurmayer R, Rimet F, Labanowski J, Vasselon V, Keck F, Illmer P, Bouchez A. 2019. Benthic diatom communities in an alpine river impacted by waste water treatment effluents as revealed using DNA metabarcoding. Front Microbiol. 10:653. doi:10.3389/fmicb.2019.00653.

Çiçek NL, Ertan ÖO. 2016. Seasonal distribution and diversity of epipelic algae in Köprüçay River (Turkey, Antalya). Acta Biol Turcica. 29:26–34.

Coste M, Boutry S, Tison-Rosebery J, Delmas F. 2009. Improvements of the Biological Diatom Index (BDI): description and efficiency of the new version (BDI-2006). Ecol Indic. 9(4):621–650. doi:10.1016/j.ecolind.2008.06.003.

Cox EJ. 2003. *Placoneis* Mereschkowsky (Bacillariophyta) revisited: resolution of several typification and nomenclatural problems, including the generitype. Bot J Linn Soc. 141(1):53–83. doi:10.1046/j.1095-8339.2003.00115.x.

Crawford RM. 1975. The taxonomy and classification of the diatom genus Melosira C.Ag. I. The type species M. nummuloides C.Ag. Br Phycol Jl. 10(4):323–338. doi:10.1080/00071617500650351.

Dallas H. 2018. Water temperature and riverine ecosystems: an overview of knowledge and approaches for assessing biotic responses, with special reference to South Africa. Water SA. 34(3):393. doi:10.4314/wsa.v34i3.180634.

Dalu T, Chauke R. 2020. Assessing macroinvertebrate communities in relation to environmental variables: the case of Sambandou wetlands, Vhembe Biosphere Reserve. Appl Water Sci. 10(1):16. doi:10.1007/s13201-019-1103-9.

Dalu T, Richoux NB, Froneman PW. 2016. Distribution of benthic diatom communities in a permanently open temperate estuary in relation to physico-chemical variables. S Afr J Bot. 107:31–38. doi:10.1016/j.sajb.2015.06.004.

Dell'uomo A. 1996. Assessment of Water Quality of an Apennine River as a Pilot Study for Diatom-based Monitoring of Italian Water courses. In: Use of Algae for Monitoring Rivers. Institut Fur Botanik, Universitàt: Vienna, Austria; p. 65–72.

Dudgeon D. 2019. Multiple threats imperil freshwater biodiversity in the Anthropocene. Curr Biol. 29 (19):960–967. doi:10.1016/j.cub.2019.08.002.

Fan X, Cui B, Zhang K, Zhang Z, Shao H. 2012. Water quality management based on division of dry and wet seasons in pearl river delta, China. Clean Soil Air Water. 40(4):381–393. doi:10.1002/clen.201100123.

Figueroa-Nieves D, McDowell WH, Potter JD, Martínez G, Ortiz-Zayas JR. 2014. Effects of sewage effluents on water quality in tropical streams. J Environ Qual. 43(6):2053. doi:10.2134/jeq2014.03.0139.

Fourtanier E, Kociolek JP. 1999. Catalogue of the diatom genera. Diatom Res. 14:1–190.

Gasse F. 1986. East African diatoms: taxonomy, ecological distribution. Bibliotheca Diatomologica. 11:201.

Gichana Z, Njiru M, Raburu PO, Masese FO. 2015. Effects of human activities on benthic macroinvertebrate community composition and water quality in the upper catchment of the Mara River Basin,Kenya. Lakes & Reservoirs: Res Manag. 20(2):128–137. doi:10.1111/lre.12094.

Göthe E, Angeler DG, Gottschalk S, Löfgren S, Sandin L. 2013. The Influence of Environmental, Biotic and Spatial Factors on Diatom Metacommunity Structure in Swedish Headwater Streams. Plos One. 8:e72237.

Guiry MD, Guiry GM 2021. AlgaeBase. Galway: Worldwide electronic publication, National University of Ireland. accessed 2021 Aug 14 http://www.algaebase.org

Haande S, Rohrlack T, Semyalo RP, Brettum P, Edvardsen B, Lyche-Solheim A, Sørensen K, Larsson P. 2011. Phytoplankton dynamics and cyanobacterial dominance in Murchison Bay of Lake Victoria (Uganda) in relation to environmental conditions. Limnol Ecol Manage Inland Waters. 41(1):20–29. doi:10.1016/j.limno.2010.04.001.

Hamdhani H, Eppehimer DE, Bogan MT. 2020. Release of treated effluent into streams: a global review of ecological impacts with a consideration of its potential use for environmental flows. Freshw Biol. 65(9):1657–1670. doi:10.1111/fwb.13519.

Hill BH, Herlihy AT, Kaufmann PR, Stevenson RJ, McCormick FH, Johnson CB. 2000. Use of periphyton assemblage data as an index of biotic integrity. J North Am Benthol Soc. 19(1):50–67. doi:10.2307/1468281.

Ice GG, Hale VC, Light JT, Muldoon A, Simmons A, Bousquet T. 2021. Understanding dissolved oxygen concentrations in a discontinuously perennial stream within a managed forest. For Ecol Manage. 479:118531. doi:10.1016/j.foreco.2020.118531.

Ifabiyi IP. 2008. Self-purification of a freshwater stream in Ile-Ife: lessons for water management. J Hum Ecol. 24 (2):131–137. doi:10.1080/09709274.2008.11906109.

Jin Z, Zhang X, Li J, Yang F, Kong D, Wei R, Huang K, Zhou B. 2017. Impact of wastewater treatment plant effluent on an urban river. J Freshwater Ecol. 32 (1):697–710. doi:10.1080/02705060.2017.1394917.

Juggins S, Kelly M, Allott T, Kelly-Quinn M, Monteith D. 2016. A water framework directive- compatible metric for assessing acidification in UK and Irish rivers using diatoms. Sci Total Environ. 568:671–678. doi:10.1016/j.scitotenv.2016.02.163.

Jyrkänkallio-Mikkola J, Siljander M, Heikinheimo V, Pellikka P, Soininen J. 2018. Tropical stream diatom communities - The importance of headwater streams for regional diversity. Ecol Indic. 95:183–193. doi:10.1016/j.ecolind.2018.07.030.

Karthick B, Taylor JC, Mahesh MK, Ramachandra TV. 2010. Protocols for collection, preservation and enumeration of diatoms from aquatic habitats for water quality monitoring in India. Icfai Uni J Soil Water Sci. 3:25–60.

Kasangaki A, Chapman LJ, Balirwa J. 2008. Land use and the ecology of benthic macroinvertebrate assemblages of high-altitude rainforest streams in Uganda. Freshw Biol. 53(4):681–697. doi:10.1111/j.1365-2427.2007.01925.x.

Kelly MG. 1998. Use of the trophic diatom index to monitor eutrophication in rivers. Water Res. 32(32):236–242. doi:10.1016/S0043-1354(97)00157-7.

Kelly M. 2013. Data rich, information poor? phytobenthos assessment and the water framework directive. Eur J Phycol. 48(4):437–450. doi:10.1080/09670262.2013.852694.

Kelly M, Acs E, Bertrin V, Bennion H, Borics G, Burgess A, Denys L, Ecke F, Kahlert M, Karjalainen S, et al. 2014. Water Framework Directive Intercalibration Technical Report: lake Phytobenthos ecological assessment methods. EUR. Vol. 26512, Luxembourg (Luxembourg): Publications Office of the European Union; JRC88347.

Kelly M, Juggins S, Guthrie R, Pritchard S, Jamieson J, Rippey B, Hirst H, Yallop M. 2008. Assessment of ecological status in UK rivers using diatoms. Freshw Biol. 53:403–422.

Khatri N, Sanjiv Tyagi S. 2015. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. Front Life Sci. 8(1):23–39. doi:10.1080/21553769.2014.933716.

Kim D-H, Chon T-S, Kwak G-S, Lee S-B, Park Y-S. 2016. Effects of land use types on community structure patterns of benthic macroinvertebrates in streams of urban areas in the South of the Korea Peninsula. Water. 8(5):187. doi:10.3390/w8050187.

Kivrak E, Uygun A. 2012. The structure and diversity of the epipelic diatom community in a heavily polluted stream (the Akarçay, Turkey) and their relationship with environmental variables. J Freshwater Ecol. 27(3):443–457. doi:10.1080/02705060.2012.671147.

Kociolek JP. 2018. A worldwide listing and biogeography of freshwater diatom genera: a phylogenetic perspective. Diatom Res. 33(4):509–534. doi:10.1080/0269249X.2019.1574243.

KSde M, Bartozek ER, Zorzal-Almeida S, Bicudo DC, Bicudo Cede M. 2018. Taxonomy and ecology of order Surirellales (Bacillariophyceae) in tropical reservoirs in Southeastern of Brazil. Acta Limnol Bras. 30:e204.

Kumar P, Lai SH, Wong JK, Mohd NS, Kamal MR, Afan HA, Ahmed AN, Sherif M, Sefelnasr A, El-Shafie A. 2020. Review of nitrogen compounds prediction in water bodies using artificial neural networks and other models. Sustainability. 12(11):4359. doi:10.3390/su12114359.

Kushwaha VB, Agarhari M. 2017. Self-purification potential of River Rapti at Gorakhpur, Uttar Pradesh, India. Int J Eng Technol Sci Res. 4:10.

Kwadzah TK, Iorhemen OT. 2015. Assessment of the impact of abattoir effluent on the water quality of River Kaduna, Nigeria. World J Environ Eng. 3:87–94.

Kwok KW, Leung KM, Lui GS, Chu VK, Lam PK, Morritt D, Maltby L, Brock TCM, Van den Brink PJ, Warne MSJ, et al. 2007. Comparison of tropical and temperate freshwater animal species' acute sensitivities to chemicals: implications for deriving safe extrapolation factors. Integr Environ Assess Manag. 3(1):49–67. doi:10.1002/ieam.5630030105

Lange-Bertalot H. 1979. Pollution tolerance of diatoms as a criterion for water quality estimation. Nova Hedwigia Beih. 64:285–304.

Law RJ. 2011. A review of the function and uses of, and factors affecting, stream phytobenthos. Freshwater Rev. 4 (2):135–166. doi:10.1608/FRJ-4.1.448.

Leps M, Sundermann A, Tonkin JD, Lorenz AW, Haase P. 2016. Time is no healer: increasing restoration age does not lead to improved benthic invertebrate communities in restored river reaches. Sci Total Environ. 557-558:722–732. doi:10.1016/j.scitotenv.2016.03.120.

Licursi M, Gómez N, Donadelli J. 2010. Ecological optima and tolerances of coastal benthic diatoms in the freshwater-mixohaline zone of the Río de la Plata estuary. Mar Ecol Prog Ser. 418:105–117. doi:10.3354/meps08865.

Licursi M, Gómez N, Sabater S. 2015. Effects of nutrient enrichment on epipelic diatom assemblages in a nutrient-rich lowland stream, Pampa Region, Argentina. Hydrobiologia. 766(1):135–150. doi:10.1007/s10750-015-2450-7.

Lund JWG. 1949. Studies on *Asterionella*: i. The Origin and Nature of the Cells Producing Seasonal Maxima. J Ecolo. 37(2):389–419. doi:10.2307/2256614.

Magurran AE. 2004. Measuring biological diversity. Malden (USA): Blackwell Publishing Co. P. p. 256.

Majaliwa JGM, Tenywa MM, Bamanya D, Majugu W, Isabirye P, Nandozi C, Nampijja J, Musinguzi P, Namusiima A, Luswata KC, et al. 2015. Characterisation of historical seasonal and annual rainfall and temperature trends in selected climatological homogenous rainfall zones of Uganda. Global J Sci Front Res: H Environ Earth Sci. 15:21–40.

Mann DG. 1999. The species concept in diatoms. Phycologia. 38(6):437–495. doi:10.2216/i0031-8884-38-6-437.1.

Marchant R. 2002. Do rare species have any place in multivariate analysis for bioassessment? J North Am Benthol Soc. 21(2):311–313. doi:10.2307/1468417.

Masouras A, Karaouzas I, Dimitriou E, Tsirtsis G, Smeti E. 2021. Benthic diatoms in river biomonitoring-present and future perspectives within the Water framework directive. Water. 13(4):478. doi:10.3390/w13040478.

Matsiko J, Mbabazi J, Ntale M. 2013. Impact of municipal effluent on the water quality of receiving rivers: a case of river aturukuku in tororo district, Eastern Uganda. Am Open Anal Chem J. 1:1–11.
McNaughton SJ. 1967. Relationships among functional properties of californian Grassland. Nature. 216 (5111):168–169. doi:10.1038/216168b0.
Mora D, Carmona J, Jahn R, Zimmermann J, Abarca N. 2017. Epilithic diatom communities of selected streams from the Lerma-Chapala Basin, Central Mexico, with the description of two new species. PhytoKeys. 88:39–69. doi:10.3897/phytokeys.88.14612.
Munir T, Hussain M, Naseem S. 2016. Water pollution - a menace of freshwater biodiversity: a review. J Entomol Zool Stud. 4:578e580.
Musonge PSL, Boets P, Lock K, Goethals PLM. 2020. Drivers of Benthic Macroinvertebrate Assemblages in Equatorial Alpine Rivers of the Rwenzoris (Uganda). Water. 12(6):1668. doi:10.3390/w12061668.
Nankabirwa A, De Crop W, Van der Meeren T, Cocquyt C, Plisnier P-D, Balirwa J, Verschuren D. 2019. Phytoplankton communities in the crater lakes of western Uganda, and their indicator species in relation to lake trophic status. Ecol Indic. 107:105563. doi:10.1016/j.ecolind.2019.105563.
Nguyen LH, Holmes S. 2019. Ten quick tips for effective dimensionality reduction. PLoS Comput Biol. 15(6): e1006907. doi:10.1371/journal.pcbi.1006907.
Nhiwatiwa T, Dalu T, Sithole T. 2017. Assessment of river quality in a subtropical Austral river system: a combined approach using benthic diatoms and macroinvertebrates. Appl Water Sci. 7(8):4785–4792. doi:10.1007/s13201-017-0599-0.
Noga T, Stanek-Tarkowska J, Kloc U, Kochman-Kędziora N, Rybak M, Ł P, Pajączek A. 2016. Diatom diversity and water quality of a suburban stream: a case study of the Rzeszów city in SE Poland. Biodivers Res Conserv. 41:19–34.
Nsubuga FW, Rautenbach H. 2018. Climate change and variability: a review of what is known and ought to be known for Uganda. Int J Clim Change Strategies Manage. 10(5):752–771. doi:10.1108/IJCCSM-04-2017-0090.
Oeding S, Taffs KH. 2017. Developing a regional diatom index for assessment and monitoring of freshwater streams in sub-tropical Australia. Ecol Indic. 80:135–146. doi:10.1016/j.ecolind.2017.05.009.
Okello W, Portmann C, Erhard M, Gademann K, Kurmayer R. 2010. Occurrence of microcystin- producing cyanobacteria in Ugandan freshwater habitats. Environ Toxicol. 25(4):367–380. doi:10.1002/tox.20522.
Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, Minchin PR, O'hara RB, Simpson GL, Solymos P, et al. 2017. Vegan: community Ecology Package. R Package Version. 2.4–2.
Onyutha C, Acayo G, Nyende J. 2020. Analyses of Precipitation and Evapotranspiration Changes across the Lake Kyoga Basin in East Africa. Water. 12(4):1134. doi:10.3390/w12041134.
Pandey J, Pandey U, Singh AV, Jaiswal D, Siddiqui E, Verma K. 2020. Atmospheric deposition and land-surface runoff driven nutrient flushing in Ganga River (India). Water Sci. 34(1):1. doi:10.1080/11104929.2020.1839344.
Park Y-S, Hwang S-J. 2016. Ecological Monitoring, assessment, and management in freshwater systems. Water. 8 (8):324. doi:10.3390/w8080324.
Patrick R. 1977. Ecology of freshwater diatoms and diatom communities. In: Werner D, editor. The biology of diatoms. Botanical Monograph. Vol. 13, Berkley: University of California Press; p. 498. 284332. 284332.
Pearce NJT, Thomas KE, Lavoie I, Chambers PA, Yates AG. 2020. Episodic loadings of phosphorus influence growth and composition of benthic algae communities in artificial stream mesocosms. Water Res. 185:116139. doi:10.1016/j.watres.2020.116139.
Pentecost A, Bailey RG, Busulwa HS, Williams A. 1997. Epilithic algal communities of the Bujuku-Mubuku river system, rwenzori mountains, Uganda. Archiv für Hydrobiologie. 139(4):479–493. doi:10.1127/archiv-hydrobiol/139/1997/479.
Pham T. 2020. Using Benthic Diatoms as a Bioindicator to Assess Rural-urban River Conditions in Tropical Area: a Case Study in the Sai Gon River, Vietnam. Pollution. 6:387–398.
Poulíčková A, Manoylov K. 2019. Ecology of freshwater diatoms - Current Trends and Applications. In: Seckbach J, Gordon R, editors. Diatoms: fundamentals and Applications. 1st ed. Beverly: Scrivener Publishing LLC; p. 289–309.
R Core Team. 2020. A language and environment for statistical computing. Vienna (Austria): R Foundation for Statistical Computing. https://www.R-project.org .
Rajwa-Kuligiewicz A, Bialik RJ, Rowiński PM. 2015. Dissolved oxygen and water temperature dynamics in lowland rivers over various timescales. J Hydrol Hydromech. 63 (4):353–363. doi:10.1515/johh-2015-0041.
Richards J, Tibby J, Barr C, Goonan P. 2020. Effect of substrate type on diatom-based water quality assessments in the Mount Lofty Ranges, South Australia. Hydrobiologia. 847 (14):3077–3090. doi:10.1007/s10750-020-04316-9.
Round FE. 1981. The ecology of algae. Cambridge (UK): Cambridge University Press. P. p. 653.
Round FE. 1991. Diatoms in river water-monitoring studies. J Appl Phycol. 3(2):129–145. doi:10.1007/BF00003695.
Round FE, Crawford RM, Mann DG. 1990. The Diatoms: biology and morphology of the genera. Cambridge: Cambridge University Press. p. 747.
Sabater S. 2009. The diatom cell and its taxonomical entity. Encycl Inland Waters. 1:149–156.
Sabater S, Elosegi A. 2014. Balancing conservation needs with uses of river ecosystems. Acta Biol Colomb. 19:3e10.
Sarkinnoma A, Yarkasuwa CI, Modu KA, Balewa AT. 2013. Analysis of Physicochemical Parameters of Sewage Water used for Irrigation in Bauchi Metropolis-Nigeria. J Environ Earth Sci. 3:10.
Schneider SC, Kahlert M, Kelly MG. 2013. Interactions between pH and nutrients on benthic algae in streams and consequences for ecological status assessment and species richness patterns. Sci Total Environ. 444:73–84. doi:10.1016/j.scitotenv.2012.11.034.
Shade A. 2017. Diversity is the question, not the answer. ISME J. 11(1):1–6. doi:10.1038/ismej.2016.118.

Sharifinia M, Mahmoudifard A, Gholami K, Namin JI, Ramezanpour Z. 2015. Benthic diatom and macroinvertebrate assemblages, a key for evaluation of river health and pollution in the Shahrood River, Iran. Limnology. 17 (1):95–109. doi:10.1007/s10201-015-0464-5.

Sládecek V. 1973. System of water quality from a biological point of view. Archiv fur Hydrobiologie-Beiheft Ergebnisse der Limnologie. 7:1–218.

Soininen J, Teittinen A. 2019. Fifteen important questions in the spatial ecology of diatoms. Freshw Biol. 64 (11):2071–2083. doi:10.1111/fwb.13384.

Solak CN, Peszek Ł, Yilmaz E, Ergül HA, Kayal M, Ekmekçi F, Várbíró G, Yüce AM, Canli O, Biniciet MS, et al. 2020. Use of Diatoms in Monitoring the Sakarya River Basin, Turkey. Water. 12(3):703. doi:10.3390/w12030703

Stevenson RJ, Bothwell ML, Lowe RL. 1996. Algal Ecology: freshwater Benthic Ecosystem. San Diego: Academic Press. p. 753.

Stevenson RJ, Pan Y, Dam VH. 2010. Assessing environmental conditions in rivers and streams with diatoms. In: Smol JP, Stoermer EF, editors. The Diatoms: applications for the environmental and earth sciences. Cambridge: Cambridge University Press; p. 469. 5785. 5785.

Stevenson RJ, Smol JP. 2003. Use of algae in environmental assessments. Freshwater Algae North Am. 775–804.

Tailor JC, Harding WR, Archibald CGM 2007a. A Methods Manual for the Collection, Preparation and Analysis of Diatom Samples Version 1.0. WRC Report TT 281/07. Pretoria (South Africa): Water Research Commission. 59.

Tailor JC, Harding WR, Archibald CGM 2007b. An Illustrated Guide to Some Common Diatom Species from South Africa. WRC Report TT 282/07. Pretoria (South Africa): Water Research Commission. P. 225.

Tanaka Y, Minggat E, Roseli W. 2021. The impact of tropical land-use change on downstream riverine and estuarine water properties and biogeochemical cycles: a review. Ecol Processes. 10:40.

Taniwaki RH, Matthaei CD, Cardoso TKM, Ferraz SFB, Martinelli LA, Piggott JJ. 2019. The effect of agriculture on the seasonal dynamics and functional diversity of benthic biofilm in tropical headwater streams. Biotropica. 51(1):18–27. doi:10.1111/btp.12617.

Tornés E, Mor J-R, Mandaric L, Sabater S. 2018. Diatom responses to sewage inputs and hydrological alteration in Mediterranean streams. Environ Pollut. 238:369–378. doi:10.1016/j.envpol.2018.03.037.

Triest L, Lung'ayia H, Ndiritu G, Beyene A. 2012. Epilithic diatoms as indicators in tropical African rivers (Lake Victoria catchment). Hydrobiologia. 695(1):343–360. doi:10.1007/s10750-012-1201-2.

UN Environment. 2018. A Framework for Freshwater Ecosystem Management. Volume 4: scientific Background. Nairobi (Kenya): UN Environment Programme. P. p. 340.

UNEP-GEMS. 2008. Water quality for ecosystem and human health. A Report. 2nd edn. Ontario: United Nations Environment Programme (UNEP) – Global Environment Monitoring Systems (UNEP-GEMS).120.

USEPA. 2013. National rivers and streams assessment 2013-2014: field operations manual – wadeable. Washington (D. C): U.S. Environmental Protection Agency (USEPA), Office of Water. p. 163. EPA-841-B-12-009b.

Veraart AJ, Romaní AM, Tornés E, Sabater S. 2008. Algal response to nutrient enrichment in forested oligotrophic stream. J Phycol. 44(3):564–572. doi:10.1111/j.1529-8817.2008.00503.x.

Vieira TB, Tejerina-Garro FL. 2014. Assessment of fish assemblages in streams of different orders in the Upper Paraná River basin, Central Brazil. Iheringia, Série Zoologia. 104 (2):175–183. doi:10.1590/1678-476620141042175183.

Wang X, Zheng B, Liu L, Li L. 2014. Use of Diatoms in River Health Assessment. Annu Res Rev Biol. 4(24):4054–4074. doi:10.9734/ARRB/2014/11963.

Yang Y, Chen H, Abdullah Al M, Ndayishimiye JC, Yang JR, Isabwe A, Luo A, Yang J. 2022. Urbanization reduces resource use efficiency of phytoplankton community by altering the environment and decreasing biodiversity. J Environ Sci. 112:140–151. doi:10.1016/j.jes.2021.05.001.

Yang -Y-Y, Toor GS, Araujo MTF, Martins Filho AJ, de Alcantara BN, Araujo FMC, Queiroz MGL, Cruz ACR, Vasconcelos BHB, Chiang JO. 2018. Stormwater runoff driven phosphorus transport in an urban residential catchment: implications for protecting water quality in urban watersheds. Sci Rep. 8(1):1. doi:10.1038/s41598-017-17765-5.

Yu J, Ning K, Li Y, Du S, Han G, Xing Q, Wu H, Wang G, Gao Y. 2014. Wet and Dry Atmospheric Depositions of Inorganic Nitrogen during Plant Growing Season in the Coastal Zone of Yellow River Delta. Sci World J. 2014:1–8.

Zimmermann J, Abarca N, Enk N, Skibbe O, Kusber W-H, Jahn R. 2014. Taxonomic Reference Libraries for Environmental Barcoding: a Best Practice Example from Diatom Research. PLoS One. 9(9):e108793. doi:10.1371/journal.pone.0108793.