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Effects of the urbanization gradient on water quality and benthic macroinvertebrates in the lakes of Bongouanou (Côte d'Ivoire)

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Abstract

Urbanization is a major driver of degradation of continental aquatic ecosystems. This study assessed the effects of the urbanization gradient on water quality and the structure of benthic macroinvertebrate communities in three lakes of the Bongouanou Department (Côte d'Ivoire): Sokotè, Kaby, and Ehuikro. Environmental variables of the water (temperature, dissolved oxygen, pH, conductivity, depth, transparency, orthophosphates, and nitrates) as well as habitat characteristics were measured monthly from May 2017 to April 2018. Benthic macroinvertebrates were sampled using a Van Veen grab, while those associated with macrophytes were collected using a dip net and identified at the generic level. The results revealed marked contrasts among the lakes. The urban lakes Sokotè and Kaby exhibited high conductivity and nutrient concentrations, associated with low dissolved oxygen levels, low water transparency, and shallow depths. In contrast, the peri-urban Lake Ehuikro was characterized by deeper, better oxygenated, and more transparent waters, with low nutrient concentrations. A total of 75 benthic macroinvertebrate taxa were recorded, with higher taxonomic richness in Lake Ehuikro (52 taxa). The communities of Sokotè and Kaby were dominated by pollution-tolerant taxa, whereas Lake Ehuikro was dominated by pollution-sensitive taxa. Redundancy analysis highlighted strong relationships between macroinvertebrate distribution and environmental variables, emphasizing the impact of urbanization on the ecological quality of lakes.

Keywords: Urbanization, benthic fauna, bioindicators, ecological water quality, lacustrine environment

Introduction

Lakes constitute essential surface water resources and play a major role in drinking water supply, agriculture, livestock farming, and various socio-economic activities (Da Costa *et al*., 1998; Da Costa and Dietoa, 2007) [1, 2]. In Côte d'Ivoire, artificial lakes represent important freshwater reservoirs widely used for irrigation, artisanal fishing, and, in some cases, as potential sources of water for human consumption (Goli Bi *et al*., 2019) [3]. However, these hydrosystems are increasingly subjected to anthropogenic pressures related to urbanization, agriculture, and livestock activities, which may alter their ecological quality. In the Bongouanou Department, the lakes Sokotè, Kaby, and Ehuikro exhibit contrasting patterns of land use and levels of disturbance. Lake Sokotè, located in the city center, is highly exposed to domestic wastewater discharges. In contrast, Lake Kaby is situated in a more remote area with limited urbanization, while Lake Ehuikro, located on the urban periphery, represents a strategic water body for domestic and agricultural uses. These spatial differences are likely to influence water physicochemical quality and the structure of aquatic communities (Kouadio *et al*., 2019) [4].

Excessive nutrient inputs from agricultural fertilizers, domestic effluents, inadequate sanitation systems, and animal waste can lead to progressive water quality degradation and disrupt aquatic ecosystems (Amoatey and Baawain, 2019) [5]. At high concentrations, these nutrients pose environmental and health risks, affecting aquatic biodiversity and increasing the mortality of sensitive species. In this context, aquatic macroinvertebrates are considered relevant bioindicators of freshwater ecological quality due to their diversity, sedentary nature, and sensitivity to environmental changes (Rosenberg and Resh, 1993; Barbour *et al*., 1999) [6,7].

Macroinvertebrates play a fundamental role in aquatic ecosystem functioning through organic matter decomposition and nutrient recycling, belonging to various functional feeding groups such as shredders, filter feeders, collectors, and predators (Tachet *et al*., 2010) [8]. Their spatial distribution is closely linked to environmental conditions and habitat modifications, making them effective indicators of ecological disturbances (Macneil *et al.,* 2002) [9]. The main objective of this study is to assess the water quality of Lakes Sokotè, Kaby, and Ehuikro and to identify the environmental variables governing the distribution and structure of aquatic macroinvertebrate communities, in order to provide scientific information useful for the sustainable management of these lacustrine ecosystems.

Materials and Methods

Study Area

The study was conducted in three lakes located in the Bongouanou Department, eastern Côte d'Ivoire (Figure 1). Lakes Sokotè and Kaby are situated in an urban environment, whereas Lake Ehuikro is located in a peri-urban area.

Lake Sokotè, located between latitudes 6°39'06.00″ and 6°39'12.00″ N and longitudes 4°12'20.00″ and 4°12'32.00″ W, is a sacred artificial lake covering approximately 15,000 m². It is mainly supplied by groundwater sources and surface runoff during the rainy season. The lake receives domestic wastewater and household solid waste.

Lake Kaby, also artificial, is located between latitudes 6°38'48.00″ and 6°38'56.00″ N and longitudes 4°12'02.00″ and 4°11'52.00″ W, downstream of Lake Sokotè. It was developed for drinking water supply purposes and covers an area of about 35,000 m². The lake is fed by groundwater and surface runoff and is subjected to anthropogenic pressures related to agricultural activities, solid waste dumping, road construction works, and wastewater discharges.

Lake Ehuikro, located between latitudes 6°38'12.00″ and 6°38'40.00″ N and longitudes 4°09'48.00″ and 4°10'30.00″ W, is a peri-urban lake whose hydrological regime depends on the Yakpo River and Lake Kaby. The surrounding area is dominated by market gardening, poultry and pig farming, as well as rubber plantations.

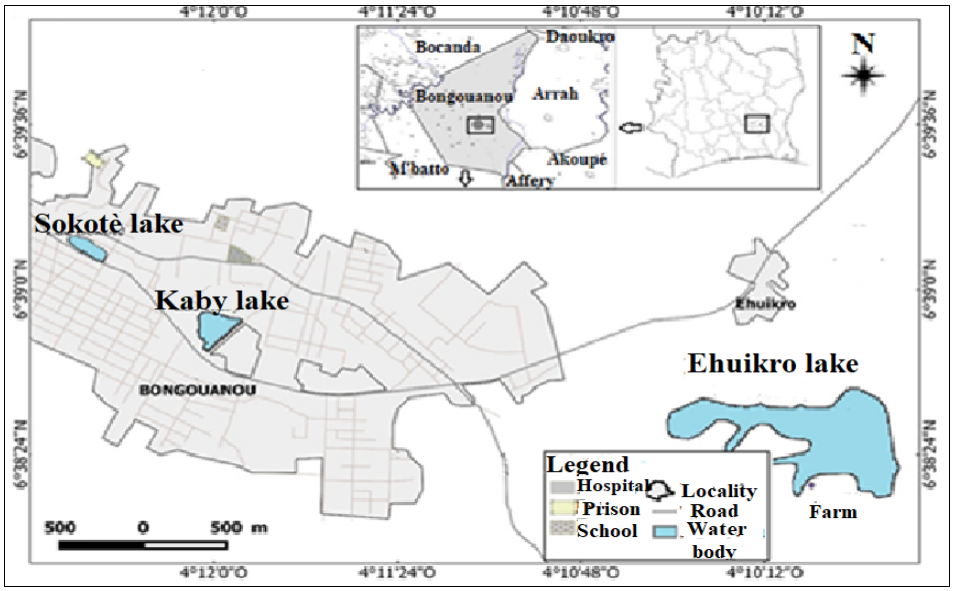

Fig 1: Geographical location of Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire)

Analysis of Environmental Variables

Physicochemical parameters were measured monthly from May 2017 to April 2018. Water temperature, dissolved oxygen, conductivity, and pH were measured in situ using an SX 713 multiparameter probe. Water transparency and depth were determined using a Secchi disk and a graduated weighted rope, respectively. Surface water samples were collected once using 500-mL polyethylene bottles and stored at 4 °C until analysis. Orthophosphate and nitrate concentrations were determined by colorimetric methods using a HACH DR/2800 spectrophotometer.

Estimation of Substrate Composition and Aquatic Plant Cover

The proportion of substrate types, namely sand, sand–gravel, gravel–mud, woody debris, and leaf litter, as well as the percentage of water surface covered by aquatic plants, were visually estimated during each sampling event. These proportions were expressed as percentages for each sampling station, following the methods proposed by Arab *et al*. (2004) [10] and Rios and Bailey (2006) [11].

Sampling and Identification of Aquatic Macroinvertebrates

Aquatic macroinvertebrates were sampled monthly using a Van Veen grab, simultaneously with physicochemical measurements. Ten random samples were collected from different habitats at each site, covering a total sampled area of 0.5 m². Visible organisms were manually removed in the field and preserved in 5% formalin. Macroinvertebrates associated with macrophytes were collected using a dip net. After washing the sediments through a 500 µm mesh sieve, the organisms were sorted and identified to the generic level under a stereomicroscope using the identification keys of Belleg (1981) [12], Dejoux *et al*. (1981) [13], Diomandé *et al.* (2000) [14], and Tachet *et al*. (2010) [8].

Data Analysis and Processing

Taxonomic richness was determined for each lake, and the collected data were analyzed using the relative abundance of individuals (N = Ni/Nt × 100), where Ni represents the number of individuals of a given taxonomic group (taxon, family, or order) and Nt is the total number of individuals in a given environment.

Redundancy Analysis

Redundancy Analysis (RDA) was used to identify potential relationships between taxon distribution and environmental variables in order to characterize species habitats. To this end, three data matrices (species × sites and environmental variables × sites) were constructed based on the absolute numerical abundances of the different species. In this analysis, environmental variables influencing macroinvertebrate taxa were selected according to their associated factor loadings. Variables with absolute factor loading values greater than 0.8 were considered to have a significant influence (Villanueva, 2004) [15]. Numerical abundances and environmental variable values were log-transformed [log (x + 1)] to achieve normality. The analysis was performed using the software CANOCO (Canonical Community Ordination), version 4.5.

Results

Environmental Variables

Table I presents the mean values of the environmental variables recorded in the different lakes. Mean water temperature ranged from 27.47 ± 1.5 °C in Lake Kaby to 28.05 ± 1.04 °C in Lake Ehuikro. The highest mean

dissolved oxygen concentration (4.82 ± 2.08 mg/L) was measured in Lake Ehuikro, whereas the lowest mean value (2.41 ± 2.17 mg/L) was recorded in Lake Sokotè. The lowest mean pH value (7.08 ± 0.51) was observed in Lake Sokotè, while the highest (7.57 ± 0.50) occurred in Lake Ehuikro. The minimum mean conductivity (277.01 ± 47.95 µS/cm) was measured in Lake Ehuikro, whereas the maximum mean conductivity (420.33 ± 164.11 µS/cm) was recorded in Lake Sokotè. The lowest mean values of water depth (0.52 ± 0.08 m) and transparency (0.17 ± 0.61 m) were observed in Lake Sokotè, while the highest values for these abiotic parameters (3.30 ± 0.94 m and 0.56 ± 0.11 m, respectively) were recorded in Lake Ehuikro. Low concentrations of orthophosphates (0.02 ± 0.01 µg/L) and nitrates (0.01 ± 0.01 µg/L) were measured in Lake Ehuikro. In contrast, high concentrations of these nutrients were recorded in Lake Sokotè (55.3 ± 50.52 µg/L) and Lake Kaby (27.08 ± 17.63 µg/L), respectively.

Table 1: Mean values of environmental variables measured in Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire)

		Lakes	
Environmental variables	**Sokotè**	**Kaby**	**Ehuikro**
Temperature (°C)	27,61±1,78	27,47± 1,5	28,05±1,04
Dissolved oxygen (mg/L)	2,41±2,17	3,17±1,42	4,82±2,08
Hydrogen potential (pH)	7,08±0,51	7,20±0,47	7,57±0,5
Conductivity (µS/cm)	420,33±164,11	344,84±140,06	277,01±47,95
Water depth (m)	0,52±0,08	1,14±0,14	3,39±0,94
Water transparency (m)	0,17±6,1	0,23±6,03	0,56±0,11
Orthophosphates (µg/L)	55,3±58,52	18,66±7,79	0,02±0,01
Nitrates (µg/L)	22,9±16,61	27,08±17,63	0,01±0,01

Estimation of Substrate Composition and Aquatic Plant Cover

The substrates of Lakes Sokotè and Kaby were dominated by gravel–mud mixtures, accounting for 80% in Lake Sokotè and 62.5% in Lake Kaby. In Lake Ehuikro, plant debris constituted the most abundant substrate type, representing 27.67% of the total. Unlike Lakes Sokotè and Kaby, Lake Ehuikro exhibited a higher aquatic plant cover, with a proportion of 26.67%.

Composition of Benthic Macroinvertebrates

A total of 40 families and 75 taxa were recorded across all lakes. In Lake Sokotè, 35 taxa belonging to 23 families were inventoried. Lake Kaby harbored 44 taxa distributed among 29 families, whereas Lake Ehuikro exhibited the highest diversity, with 52 taxa and 32 families (Table II). Only families and taxa with a relative abundance greater than 5% of the total abundance in each lake were considered in the analysis. At the family level, Thiaridae (52.73% and 40.21%), Chironomidae (22.32% and 14.61%), and Tubificidae (20.24% and 31.35%) dominated the assemblages in Lakes Sokotè and Kaby, respectively. In Lake Ehuikro, Baetidae were the most dominant family (19.85%) (Figure 2). At the taxon level, *Melanoides tuberculata* dominated the assemblages in Lakes Sokotè (52.73%) and Kaby (45.74%). In contrast, *Baetis* sp., with a relative abundance of 19.85%, dominated the assemblage in Lake Ehuikro (Figure 3).

Table 2: List of benthic macroinvertebrate taxa sampled in Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire) from May 2017 to April 2018

		Lakes		
Families	**Taxa**	**Sokotè**	**Kaby**	**Ehuikro**
Glossiphoniidae	*Haementeria costata*	+	+	
	Helobdella stagnalis		+	
	Hemiclepsis marginata	+	+	+
Lumbricidae	*Lumbricus* sp.			+
Lumbriculidae	*Lumbriculus* sp.	+	+	
Tubificidae	*Tubifex* sp.	+	+	+
Hydrachnidae	*Hydrachna globosa*		+	+
Chrysomelidae	*Pyrralta* sp.	+		
Dryopidae	*Dryops* sp.		+	
	Pomatinus sp.		+	
Dytiscidae	*Dytiscus* sp.		+	
	Hydrovatus sp.			+
	Laccophilus luctuosus	+	+	+
	Laccophilus sp.	+	+	+
Hydrophilidae	*Amphiops* sp.		+	+
	Coelostoma sp.			+
	Helochares sp.	+	+	+
	Hydrobius sp.			+
	Laccobius sp.	+	+	+
Noteridae	*Noterus* sp.		+	+

Ceratopogonidae	*Bezzia* sp.			+
	Ceratopogon sp.	+		
Chaoboridae	*Chaoborus* sp.			+
Chironomidae	*Chironomus formosipennis*	+	+	+
	Corynoneura sp.			+
	Nilodorum fractilobus	+	+	+
	Polypedilum sp.	+	+	+
Culicidae	*Culex* sp.	+	+	+
Ephydridae	*Hydrellia* sp.	+	+	
Limoniidae	*Hexatoma* sp.	+		
Psychodidae	*Clogmia albipunctata*		+	
	Psychoda sp.		+	
Scatophagidae	*Acanthocnema glaucescens*		+	
	Acanthocnema sp.		+	
Sciomyzidae	*Sciomyza* sp.		+	
Stratiomyidae	*Hermetia illucens*		+	
	Odontomyia sp.	+	+	+
Syrphidae	*Eristalis* sp.	+	+	+
+ = présence				

Continuation of Table II

				Lakes	
	Families	**Taxa**	**Sokotè**	**Kaby**	**Ehuikro**
	Baetidae	*Baetis* sp.	+	+	+
	Belostomatidae	*Belostoma* sp.		+	+
		Diplonychus sp.	+	+	+
	Corixidae	*Micronecta scutellaris*		+	+
	Gerridae	*Gerris* sp.			+
	Mesoveliidae	*Mesovelia* sp.			+
	Naucoridae	*Macrocoris flavicolis*			+
		Naucoris sp.			+
	Népidae	*Nepa rubra*		+	
		Ranatra linearis	+	+	+
	Notonectidae	*Anisops* sp.	+	+	+
	Pleidae	*Plea* sp.		+	+
	Crambidae	*Elophila* sp.		+	
		Parapoynx sp.			+
	Coenagrionidae	*Ischnura* sp.	+	+	+
		Pseudagrion punctum	+		+
		Coeriagrion tenellum			+
	Corduliidae	*Epitheca bimaculata*	+		+
		Somatochlora sp.	+		+
		Somatochlora flavomaculata	+		
		Cordulia aenea			+
		Oxygastra curtisii			+
	Libellulidae	*Brachythemis leucosticta*			+
		Orthetrum sp.			+
	Bulinidae	*Bulinus forskalii*	+	+	+
		Bulinus truncatus	+	+	+
	Lymnaeidae	*Lymnaea natalensis*		+	+
	Physidae	*Physa marmorata*		+	+
	Planorbidae	*Biomphalaria pfeifferi*	+	+	+
		Gyraulus sp.	+		
		Helisoma sp.	+		
	Pilidae	*Lanistes libycus*			+
		Lanistes sp.			+
		Lanistes varicus			+
		Pila africana	+		
		Pila ovata	+		
	Thiaridae	*Melanoides tuberculata*	+	+	+
	40	75	35	44	52
	+= présence				

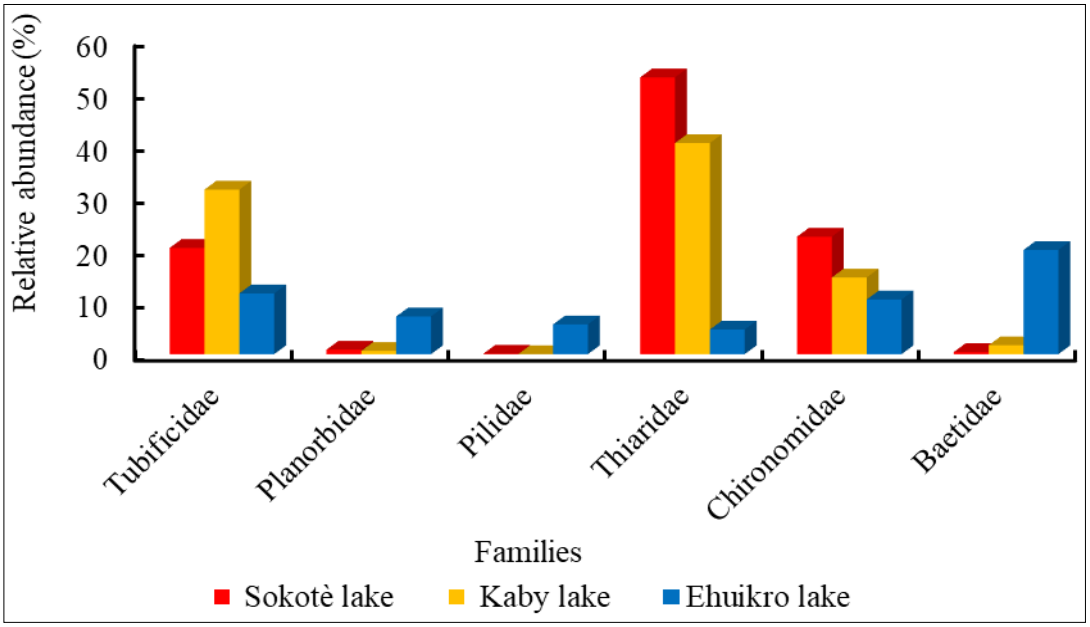

Fig 2: Relative abundance of benthic macroinvertebrate families sampled in Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire)

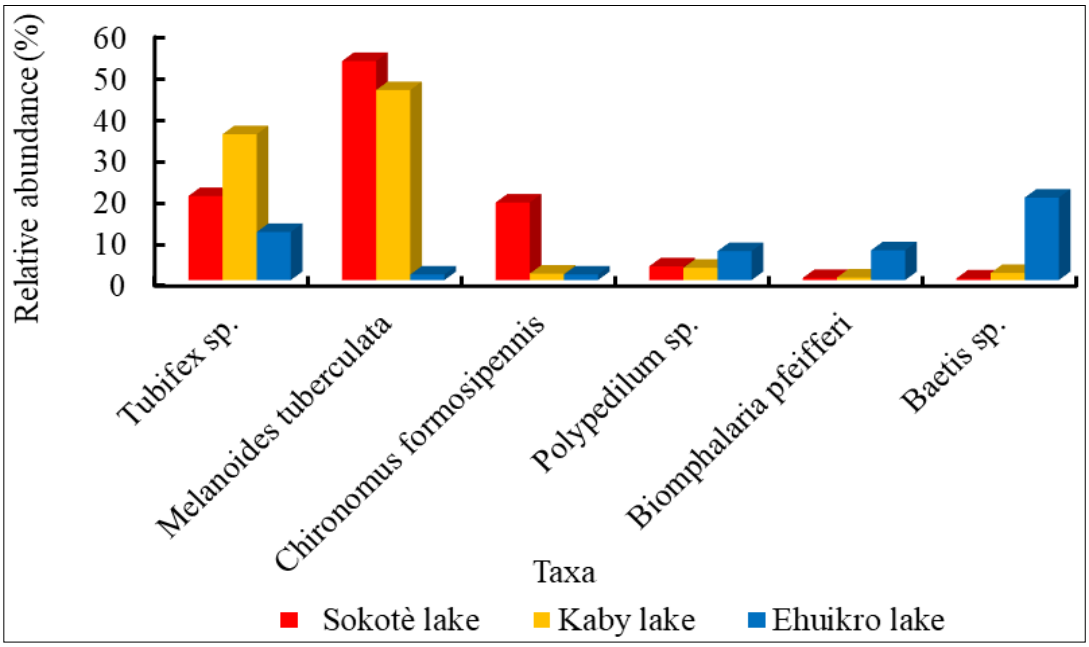

Fig 3: Relative abundance of benthic macroinvertebrate taxa sampled in Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire)

Influence of Environmental Variables on Taxa Distribution

The influence of abiotic parameters on the abundance of the main benthic macroinvertebrate taxa was assessed using Redundancy Analysis (RDA). The taxa considered in this analysis were those representing at least 2% of the total abundance in each lake. The results showed that the relationships between environmental factors and the main taxa were mainly explained by the first two axes (Axis 1 and Axis 2). These axes accounted for 95.3% of the cumulative variance of the taxon data and were therefore used for result interpretation (Figure 4). The influence of abiotic parameters on the distribution of benthic macroinvertebrates is presented in Table III and includes conductivity, pH, dissolved oxygen, water transparency, depth, gravel–mud substrate, plant debris, and aquatic plant cover.

Group I consisted of Lake Ehuikro and was characterized by deep and transparent waters, high pH values, and high dissolved oxygen concentrations, with substrates rich in plant debris and better aquatic plant cover. This lake was favorable to the proliferation of organisms such as *Helochares* sp., *Ischnura* sp., *Noterus* sp., *Lanistes* varicus, *Baetis* sp., *Micronecta scutellaris*, and *Biomphalaria pfeifferi.*

Group II included Lakes Sokotè and Kaby and was characterized by high conductivity and substrates dominated by gravel–mud mixtures. These lacustrine environments favored the development of organisms such as *Tubifex* sp., *Chironomus formosipennis*, *Melanoides tuberculata*, *Polypedilum* sp., *Diplonychus* sp., and *Nilodorum fractilobus*.

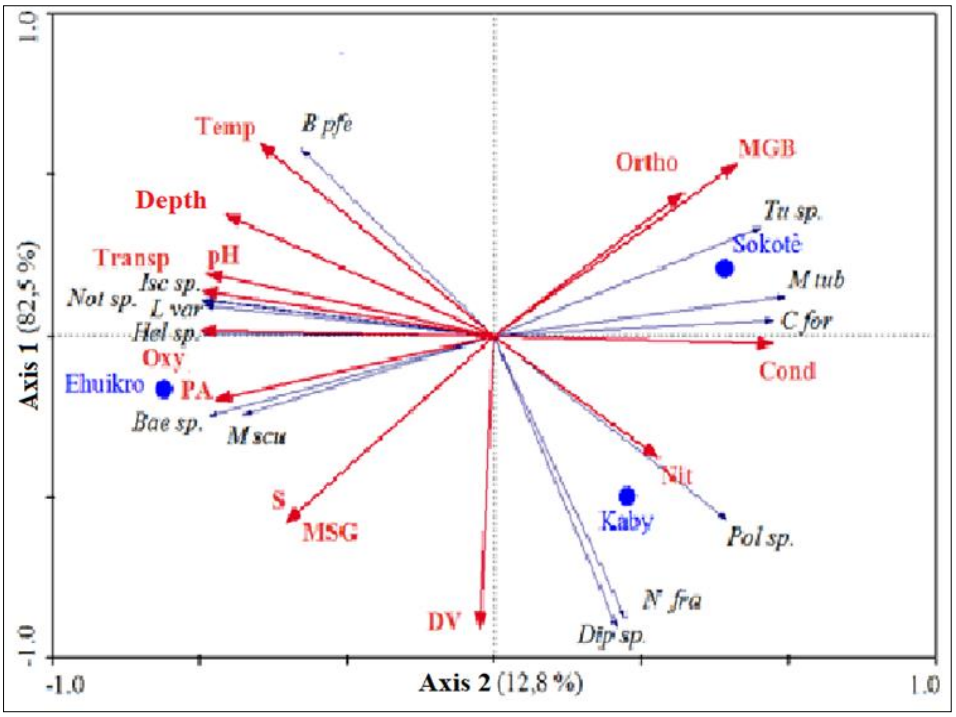

Fig 4: Results of the Redundancy Analysis (RDA) showing relationships between the main benthic macroinvertebrate taxa and abiotic variables in Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire). *Prof = Depth; Oxy = Dissolved oxygen; Temp = Temperature; Cond = Conductivity;* Transp = *Transparency; Ortho = Orthophosphates; Nit = Nitrates; PA = Aquatic plants; MSG =* Sand–gravel mixture; *MGB* = Gravel–mud mixture; *S = Sand; Hel* sp. = *Helochares* sp.; *Is* sp. = *Ischnura* sp.; *Not* sp. = *Noterus* sp.; *L var* = *Lanistes varicus*; *Bae* sp. = *Baetis* sp.; *M scu = Micronecta scutellaris*; *Tu* sp. = *Tubifex* sp.; *C for = Chironomus formosipennis*; *M tub = Melanoides tuberculata*; *Pol* sp. = *Polypedilum* sp.; *N fra = Nilodorum fractilobus*; *Di* sp. = *Diplonychus* sp.; *B pfe = Biomphalaria pfeifferi*.

Table 3: Factor loadings of environmental variables for Lakes Sokotè, Kaby and Ehuikro in the Bongouanou Department (Côte d'Ivoire) along the first two axes of the redundancy analysis. Bold values indicate environmental variables that significantly influence taxa

Environmental variables	Axis 1	Axis 2
Conductivity	-0,0224	0,9476
pH	0,1966	-0,9754
Temperature	0,5980	-0,7955
Dissolved oxygen	0,0169	-0,9956
Orthophosphates	0,4454	0,6425
Nitrates	-0,3771	0,5591
Transparency	0,1408	-0,9900
Depth	0,3790	-0,9112
Gravel-mud mixture	0,5347	0,8243
Sand-gravel mixture	-0.5779	-0.7057
Sand	-0.5779	-0.7057
Plant debris	-0.9070	-0.0475
Aquatic plants	-0.1957	-0.9430

Discussion

Water temperature values recorded in the three lakes reflect typical tropical conditions, as freshwater ecosystems in Côte d'Ivoire rarely experience temperatures below 25 °C (Iltis and Lévêque, 1982) [16]. The low dissolved oxygen concentration observed in Lake Sokotè indicates degraded water quality, consistent with the threshold proposed by Beaux (1998) [17]. This condition is likely linked to domestic wastewater and solid waste inputs from surrounding urban areas, which also explain the high orthophosphate concentrations recorded in this lake, as detergents in domestic effluents are known phosphate sources (Jen, 2002) [18].

All lakes exhibited slightly alkaline waters, with higher pH values in Lake Ehuikro, probably related to geological conditions and its hydrological connection with a river system flowing through calcareous soils (Igmoullan *et al*., 2001) [19]. The lower conductivity values observed in Lake Ehuikro indicate a reduced load of dissolved substances, whereas higher conductivity in Lakes Sokotè and Kaby reflects stronger anthropogenic influence. Reduced depth and transparency in Lake Sokotè are attributed to sediment accumulation from runoff, while the higher transparency of Lake Ehuikro suggests low suspended matter. Elevated nitrate concentrations in Lake Kaby are likely associated with fertilizer inputs from surrounding market gardening activities, as reported by Atanle *et al*. (2012) [20].

Macroinvertebrate assemblages clearly reflected these environmental conditions. Lake Ehuikro showed higher taxonomic richness, consistent with lower anthropogenic pressure and greater habitat stability. In contrast, Lakes Sokotè and Kaby were dominated by pollution-tolerant taxa such as Thiaridae, Chironomidae, and Tubificidae, commonly associated with organically enriched and eutrophic environments (Steinmann *et al*., 2006; Rashid and Pandit, 2014) [21, 22]. The dominance of Baetis sp. in Lake Ehuikro indicates better ecological quality, as this taxon is characteristic of well-oxygenated waters (Demoulin, 1981) [23].

Redundancy analysis confirmed strong relationships between macroinvertebrate distribution and key environmental variables. Pollution-sensitive taxa were associated with Lake Ehuikro, characterized by greater depth, higher transparency, and better oxygenation, whereas pollution-tolerant taxa were linked to Lakes Sokotè and Kaby, where high conductivity and gravel–mud substrates indicate ecological degradation. These results highlight the relevance of benthic macroinvertebrates as reliable indicators of urbanization-driven impacts on lacustrine ecosystems.

Conclusion

This study highlights the impact of the urbanization gradient on water quality and the structure of aquatic macroinvertebrate communities in the lakes of Bongouanou. The urban lakes Sokotè and Kaby exhibit clear signs of ecological degradation, characterized by high nutrient concentrations, elevated conductivity, low dissolved oxygen levels, and the dominance of pollution-tolerant taxa. In contrast, the peri-urban Lake Ehuikro, which is less exposed to anthropogenic pressures, maintains better water quality and supports a more diverse benthic fauna dominated by pollution-sensitive taxa. The observed relationships between macroinvertebrates and environmental variables confirm the relevance of these organisms as effective bioindicators of ecological quality. These findings emphasize the need for integrated management strategies aimed at reducing anthropogenic inputs in order to ensure the sustainable conservation of lacustrine ecosystems.

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