World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

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Comparative analysis of benthic macroinvertebrate communities in the upper section of Ivin do basin, Gabon

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World Journal of Advanced Research and Reviews, 2026, 30(02), 1275-1288

Publication history: Received on 04 April 2026; revised on 11 May 2026; accepted on 13 May 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.30.2.1275

Abstract

In this study we compared the structure and diversity of benthic macroinvertebrate communities, as well as the physicochemical conditions, in two sub-basins of the upper Ivin do basin that are subject to contrasting gold mining processing (artisanal and industrial). The results revealed a significant physicochemical difference ($p < 0.05$) regarding temperature, dissolved oxygen and pH, while conductivity and turbidity do not appear to be significantly different ($p > 0.05$). The sampling campaign identified 2,436 individuals and 96% of them were Arthropods. The high proportion of EPT taxa (63%) indicates that the site's ecological integrity is generally well preserved. High diversity indices indicate balanced stands and suggest that mining activities have a limited direct ecological impact in the short term. The differences observed between the two sub-basins appear to be linked to physical changes to the habitat and landscape fragmentation resulting from mining infrastructure.

Keywords: Ivin Do; Benthic Macroinvertebrates; Diversity; Impact; Gold Panning

1. Introduction

Continental aquatic ecosystems are facing increasing anthropogenic pressures worldwide, particularly due to the changes in land use, mining and climate change [1]. These disturbances affect the physicochemical and hydrological characteristics of watercourses, with direct consequences on aquatic biological communities [2]. Benthic macroinvertebrate communities are recognized as bioindicators of lotic ecosystems due to their taxonomic diversity, their relatively sedentary and their variable sensitivity to environmental disturbances [3]. Although many studies have documented the impacts of gold mining on these communities in tropical environments) [4,5], the knowledges remain fragmented for forest streams in Central Africa, particularly in Gabon. The upper Ivindo basin, located in Gabon's North-East Province, represents a river system of interest where industrial and artisanal gold mining have coexisted for a decade. The Ekata-Youkou region, where local communities practice small-scale gold panning alongside subsistence activities (farming, hunting and fishing), offers a particularly relevant context for assessing the cumulative impacts of these activities on benthic communities. This study aims to analyze and compare the composition and structure of benthic macroinvertebrate communities in two sub-watersheds of the upper Ivindo basin: the Zadié and the Moulé. More specifically, we aim to: (i) characterize the taxonomic and functional diversity of benthic communities in these

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forest streams; (ii) identify differences in stand structure between the two sub-basins; and (iii) assess the potential impact of gold mining activities on these communities. This first comparative study of benthic macroinvertebrates in this region will provide essential baseline data for the management and conservation of these tropical aquatic ecosystems.

2. Materials and methods

2.1. Characteristics of the study area

The study was carried out in the upper Ivindo basin, located in the northeastern of the village of Ekata, in the Zadié department, Ogooué-Ivindo province (0° 40' N, 14° 18' E). The village of Ekata is located approximately 70 km in the south of the department capital Mékambo. The study area extends as far as the Youkou sector including the headwaters of the Zadié and Moulé rivers and is located approximately at 20 km in the north-east of Ekata. (Figure 1). The region has an equatorial climate with four seasons, characterized by an average annual temperature of 22.7°C. July marks the height of the dry season, with average rainfall of 20.4 mm and average minimum temperatures of 22.7°C (Climate-Data.org). The vegetation is dominated by dense, evergreen rainforest, typical of the forest massif in northeastern Gabon. The two sub-basins studied have distinct histories of gold mining. The Zadié catchment area has been subject to industrial mining, whilst the Moulé catchment area has been subject to artisanal mining. The Youkou site is a gold-miners' camp mainly occupied by populations by people of Congolese origin, whose livelihoods depend on small-scale gold mining, subsistence farming, hunting and fishing. Sampling for benthic macroinvertebrates was carried out during the main dry season, from 16 to 29 July 2022. A total of 13 stations were surveyed: six stations in the Zadié catchment and seven stations in the Moulé catchment (Table 1). The sampling period was chosen to minimize seasonal hydrological variations and facilitate accessibility.

Table 1 Characteristics of the monitoring stations in the two watersheds

Station name and code	Characteristics	Photo
Moulé1 (MOL01)	Width: 3 m Maximum depth: 0.3 m Speed: 0.05 m/s Flow rate: 0.12 m^3/s A river in its natural state with sandbanks	
Moulé2 (MOL02)	Width: 2.4 m Max depth: 0.12 m Speed: 0.05 m/s Flow rate: 0.12 m^3/s A river in its natural state with sandbanks	
Moulé3 (MOL03)	Width: 6 m Max depth: 0.6 m Flow velocity: 0.05 m/s Flow rate: 0.12 m^3/s Banks lined with arrowhead plants and large trees. Predominantly sandy substrate	

Moulé4 (MOL04)	Width: 2.4 m Max depth: 0.11 m Flow velocity: 0.1 m/s Flow rate: 0.014 m^3/s A natural river; the dominant substrate is fine sand	
Moulé5 (MOL05)	Width: 1 m Max depth: 0.1 m Flow velocity: 0.01 m/s Flow rate: 0.2 m^3/s The profile of the river affected by site operations. The substrate is predominantly sandy.	
Moulé6 (MOL06)	Width: 6 m Max depth: 0.20 m Flow velocity: 0.3 m/s Flow rate: 0.25 m^3/s The profile of the river affected by operations at the site. Piles of gravel indicate recent gold panning activity	
Moulé7 (MOL07)	Width: 5.5 m Max depth: 0.34 m Flow velocity: 0.28 m/s Flow rate: 0.3 m^3/s The river's morphology bears the marks of past exploitation. The substrate consists mainly of pebbles.	
Large Moulé (GMOUL)	Width: 2.0 m Max depth: 0.2 m Speed: 0.19 m/s Flow rate: 0.29 m^3/s Bathymetric width affected by river exploitation. Former gold-panning camp; fallen trees, piles of pebbles	
Lybie (LYB01)	Width: 11.5 m Maximum depth: 0.32 m Speed: 0.05 m/s Flow rate: 0.12 m^3/s The bathymetric width has been altered by human activities. Presence of Musanga cecropioides	 Amont de la station LYB01 (zone exploitée, chenal transformé en étang)  Aval de la station LYB01

Upper Zadié (ZAD01)	Width: 2 m Max depth: 0.41 m Flow velocity: 0.3 m/s Flow rate: 0.25 m^3/s The substrate consists of gravel and pebbles. Human impacts include swimming, laundry, fishing and the soaking of cassava.	
Downstream of Zadié (ZAD02)	Width: 5.35 m Max depth: 0.69 m Flow velocity: 0.46 m/s Flow rate: 1.03 m^3/s A gently sloping river, lined with trees and vines. Fine sandy bed	
Bekogo (BEK01)	Width: 6.3 m Max depth: 0.3 m Flow velocity: 0.26 m/s Flow rate: 0.17 m^3/s River with sandbanks showing signs of human activity, evidenced by piles of gravel and pebbles, indicating gold panning	
Moignati (MOI01)	Width: 6.5 m Max depth: 0.5 m Flow velocity: 0.31 m/s Flow rate: 0.18 m^3/s A river in its natural state, with sandbanks and banks colonised by marantaceae	
Louangué (LOU01)	Width: 4.8 m Maximum depth: 0.20 m Flow velocity: 0.19 m/s Flow rate: 0.07 m^3/s A river in its natural state with sandbanks.	
Omimi (OMI01)	Width: 8.6 m Max depth: 0.3 m Speed: 0.22 m/s Flow rate: 0.13 m^3/s Rapid section with numerous boulders	

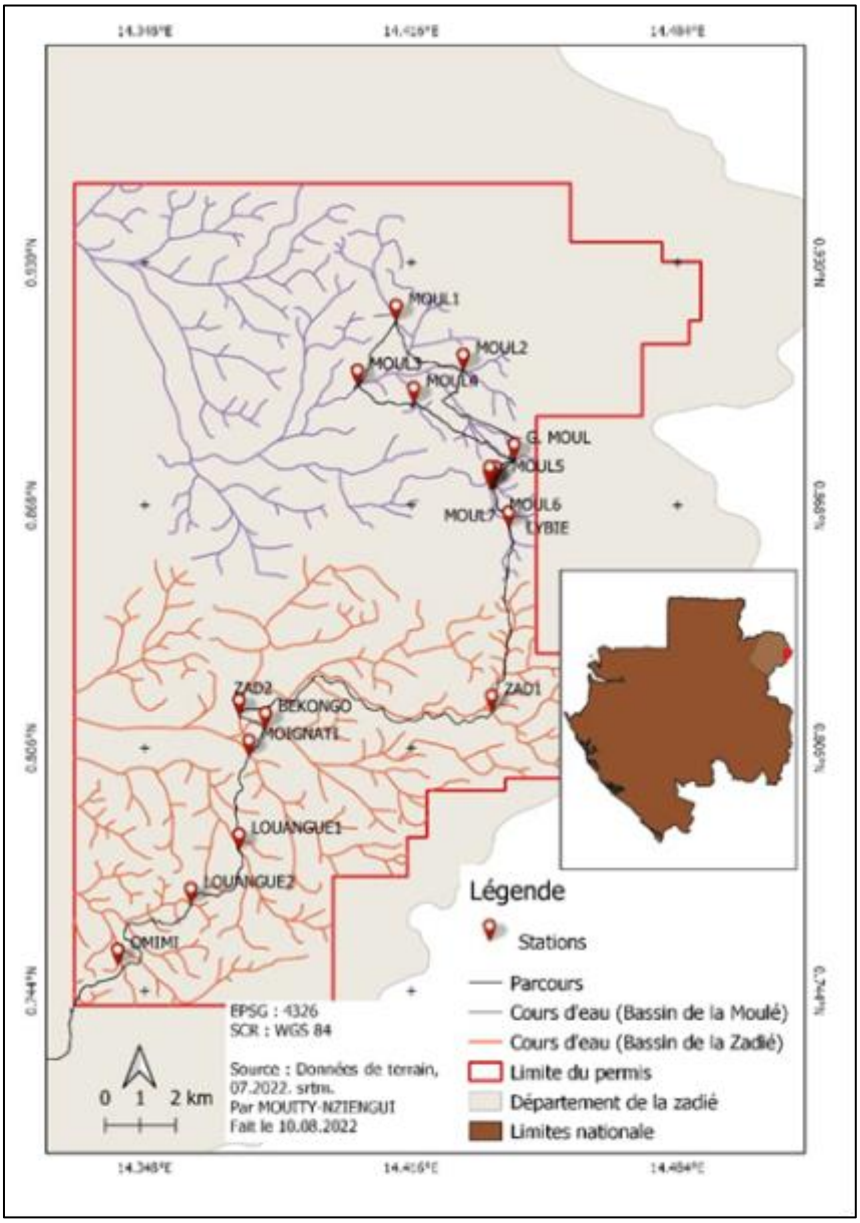

Figure 1 Location of the stations in the two watersheds

2.2. Measurement of environmental variables

The physicochemical parameters of the water were measured in situ at each station using a portable multi-parameter probe (HI9829, Hanna Instruments). The variables recorded included: temperature (°C), pH, total dissolved solids (TDS, mg/L), electrical conductivity (µS/cm), dissolved oxygen (DO, % saturation) and turbidity (NTU).

In accordance with the recommendations ([3] and [4], all measurements were taken between 8.00 am and 9.00 am to minimize diurnal variations. Measurements were taken in the center of the stream, at mid-depth, taking care to avoid areas of eddy and excessive sedimentation.

2.3. Sampling of benthic macroinvertebrates

Benthic macroinvertebrates were collected using a Surber net (sampling area: 0.09 m^2; mesh size: 500 µm). In each station, five replicates were collected from representative habitats (rocky, sandy and organic substrates). The samples were sorted in the field to separate the macroinvertebrates from organic matter and sediment, then fixed in 96% ethanol for preservation. Taxonomic identification was carried out at the Hydrobiology and Ichthyology Laboratory (LHI) of the Institute of Agronomic and Forestry Research (IRAF) at Libreville, using the identification keys [5], [6], [7], [8], [9] and [10]. Identification was performed at the finest possible taxonomic level, generally at the genus or species level.

2.4. Statistical analyses

The structure and diversity of benthic macroinvertebrate communities were characterized using several indices calculated with Past (version 4.11) and RStudio (R4.5.2) software. Total abundance (N): total number of individuals per site. Taxonomic richness (S): the total number of taxa identified per site. The Shannon-Weaver diversity index (H') [11]:]: $H' = -\Sigma (pi \times \ln pi)$ where pi is the proportion of taxon i in the sample. Pielou's evenness (J) [12]: $J = H' / \ln(S)$ where S is the taxonomic richness. This index ranges from 0 to 1; values close to 1 indicate a homogeneous distribution of abundances among taxa [13]. Simpson's dominance index (D) [14]: $D = \Sigma [ni(ni-1)] / [N(N-1)]$ where ni is the number of individuals of taxon i and N the total abundance. After testing the normality of the distributions of the biological data, the Mann-Whitney test was used to compare the differences between the two catchments. The data were standardized prior to analysis to account for differences in measurement scales.

3. Results

3.1. Physicochemical characteristics of study sites

The two watershed have distinct environmental characteristics. The six monitoring stations in the Zadie catchment recorded an average temperature of 23.28 ± 0.69 °C, ranging from 22.35 °C (OMI01) to 24.35 °C (ZAD01). The average dissolved oxygen level was 19.04 ± 4.37%, with values ranging from 14.05% (MOI01) to 24.22% (BEK01 and ZAD02). The average pH was slightly alkaline (7.36 ± 0.06), ranging from 7.31 (ZAD01) to 7.44 (MOI01). The average electrical conductivity was 44.26 ± 13.18 µS/cm, with a minimum of 26.53 µS/cm (LOI02) and a maximum of 67.30 µS/cm (ZAD01). The average turbidity was 21.03 ± 1.69 NTU, varying slightly between stations (20.20 NTU at ZAD01 and 23.27 NTU at MOI01).

The seven stations in the Moule basin showed a slightly lower average temperature (22.14 ± 0.26 °C), with values ranging from 21.65 °C (GMOU01) to 22.44 °C (MOU03). The dissolved oxygen level was significantly lower (9.17 ± 1.17%), ranging from 7.77% (MOU07) to 11.09% (MOU04). The average pH was higher (7.84 ± 0.24), with values ranging from 7.42 (MOU03) to 8.23 (GMOU01).

The average electrical conductivity was higher (66.30 ± 31.72 µS/cm), showing considerable variability between stations: 24.61 µS/cm (MOU02) to 105.89 µS/cm (GMOU01). The average turbidity was also higher (22.96 ± 6.18 NTU), with a significant range from 15.37 NTU (MOU03) to 32.74 NTU (MOU04).

3.2. Comparison between basins

The non-parametric Kruskal-Walli's test reveals significant differences (Figure 2) between the two catchments for three parameters: temperature ($U = 0.002127$, $p < 0.05$), dissolved oxygen ($U = 0.0009894$, $p < 0.05$) and pH ($U = 0.001765$, $p < 0.05$). In contrast, no significant differences were observed for electrical conductivity ($H = 0.266$, $p > 0.05$) and turbidity ($H = 0.9578$, $p > 0.05$), despite higher mean values and variances in the Moulé catchment. The main contrasts between the two basins concern dissolved oxygen (twice as high in the Zadié basin), pH (more alkaline in the Moulé basin), electrical conductivity (1.5 times higher in the Moulé basin with three times greater variability), and turbidity (higher and more variable in the Moulé basin). These differences suggest distinct levels of disturbance linked to the types of gold mining practiced in each basin.

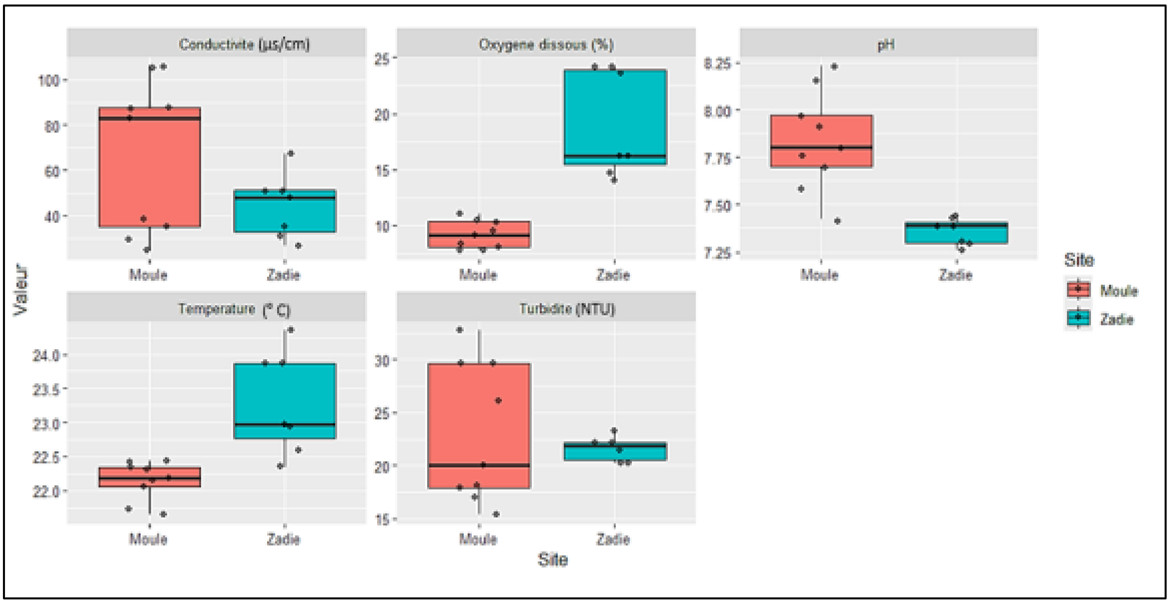

Figure 2 Average values of the physicochemical parameters measured in the two watersheds

3.3. Comparison of physicochemical parameters

Pearson's (or Spearman's) correlation analysis between the physicochemical variables reveals a strong and significant positive correlation between temperature and dissolved oxygen levels (r = 0.90, $p < 0.05$) (Figure 3), indicating that the warmest stations also have the lowest oxygen concentrations. Conversely, a strong and significant negative correlation was observed between temperature and pH (r = -0.72, $p < 0.05$), suggesting that increasing temperature is accompanied by a decrease in pH in the studied streams. Similarly, a significant negative correlation was observed between pH and dissolved oxygen (r = -0.65, $p < 0.05$), indicating that indicating that as pH decreases, the saturation level of the water increases. These results indicate that the two types of gold mining (industrial vs. artisanal) generate distinct physicochemical conditions, particularly in terms of water temperature, oxygenation and water acidity.

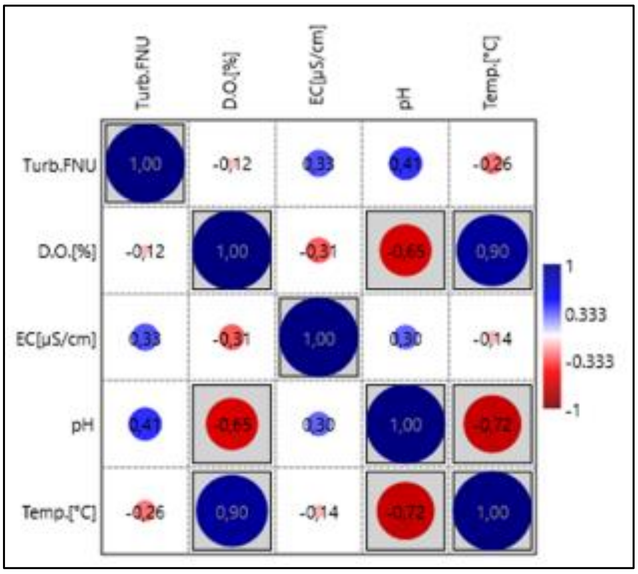

Figure 3 Results of the Pearson correlation analysis between environmental parameters

3.4. Taxonomic richness and structure of benthic macroinvertebrate communities

3.4.1. Overall taxonomic diversity

During this inventory, 2,436 benthic macroinvertebrates were collected in the 13 sampled stations: 1,551 individuals (63.7%) in the Moulé basin and 885 individuals (36.3%) in the Zadié basin. The Moulé catchment area is home to 60 taxa, comprising 2 phyla, 12 orders, 42 families and 60 genera (Appendix 1). The Zadié catchment comprises 48 taxa belonging to 4 phyla, 11 orders, 39 families and 48 genera. Table 2 presents the complete list of taxa recorded in the two watersheds. The Moulé catchment area have a rich taxonomic diversity of 60 taxa belonging to 2 phyla, 12 orders, 42 families, and 60 genera (Appendix 1). The Zadié catchment contains 48 taxa belonging to 4 phyla, 11 orders, 39 families, and 48 genera. Table 2 presents the complete list of taxa inventoried in both watersheds. In both basins, Arthropods (class Insecta) dominate the populations, representing 96.83% of the population in the Zadié and 96.45% in the Moulé. The other phyla of Mollusca (Gastropoda), Annelida (Oligocheta), and Platyhelminthes (Triclada) constitute only 3.17% and 3.55% of the total population, respectively.

3.4.2. Composition of the communities by order

On each watershed, the Ephemeroptera-Plecoptera-Trichoptera (EPT) group, considered pollution-sensitive, dominates both communities with 63% of the total cumulative abundance (Figures 4a and 4b). In the Moulé catchment (Figure 4a), the order Ephemeroptera is the most abundant, representing 39% of the total population, followed by Plecoptera (14%) and Trichoptera (10%). Diptera account for 19% of individuals, while Coleoptera (6%), Decapoda (5%) and Heteroptera (2%) are less abundant. The least represented orders are grouped under the 'Others' category (< 1%) and include Mesogasteropoda (13 individuals), Basommatophora (3 individuals), Oligochaeta (2 individuals) and Decapoda (1 individual). In the Zadié site (Figure 4b), Ephemeroptera (39%) are also dominant, followed by Plecoptera (12%) and Trichoptera (12%). Diptera account for 11% of the population, Decapoda for 9%, and Coleoptera for 8%. The "Other" category (1%) includes Basommatophora (5 individuals) and Tricladida (7 individuals).

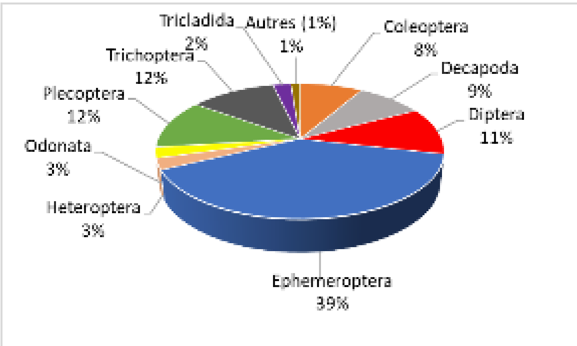

Figure 4A Relative abundance of orders at Moule

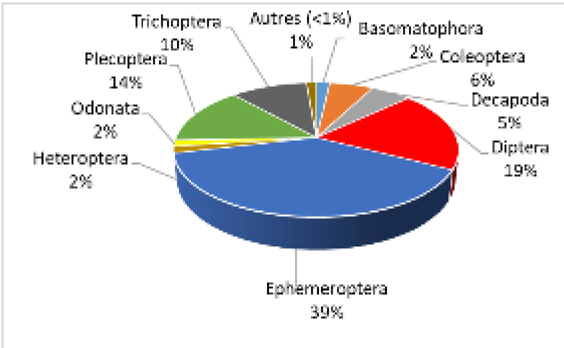

Figure 4B Relative abundance of orders at Zadie

3.5. Family diversity

The most diverse orders in terms of families differ between the two basins. In the Zadié basin, the Ephemeroptera comprise 8 families, the Trichoptera 6 families, while the Odonata, Diptera, and Coleoptera each comprise 5 families. In the Moulé basin, the Ephemeroptera exhibit the greatest family diversity with 11 families, followed by the Coleoptera (7 families), then the Diptera and Trichoptera (6 families each).

3.5.1. Statistical Comparison of macroinvertebrates communities

The non-parametric Kruskal-Walli's test (H) did not reveal a significant difference in taxonomic composition between the two watersheds ($H = 0.3374$; $p > 0.05$). However, the Moulé watershed exhibited greater taxonomic richness (57 vs. 48 taxa) and a significantly higher total abundance (1,551 vs. 885 individuals), suggesting a differential impact of the two management practices on benthic communities. Figure 3a presents the taxonomic composition of the two watersheds at the order level.

Four orders, comprising species not common to both watersheds, can be distinguished. These are the orders of Coleoptera (*Hydroplilus* sp., *Psephenus* sp., *Cyphon* sp., *Euvira* sp.), Heteroptera (*Corixa* sp., *Microvelia* sp., *Mesovelia* sp.), Odonata (*Nehalennia speciosa*, *Gomphus* sp., *Hagenia* sp.), and Trichoptera (*Anisocentropus* sp., *Arctopsyche* sp., *Parapsyche* sp., *Philopatamus* sp.). Overall, nine species are not common to both watersheds. Table 2 presents the faunal list for both watersheds.

Table 2 List and population size of benthic macroinvertebrates in the Moule and Zadié watersheds

Phylum	Class	Order	Family	Species	Moule	Zadie
Arthropoda		Decapoda	Atyidae	*Atyaephyra desmarestii*	+	+
	Insecta		Palaemonidae	*Macrobachium sp*	+	+
			Potamonidae	*Potamon sp*	+	+
		Plecoptera	Chloroperlidae	*Chloroperla sp*	+	-
			Perlidae	*Perla sp*	+	+
		Trichoptera	Calamoceratidae	*Anisocentropus sp*	+	-
				Phylloicus sp	+	+
			Goeridae	*Goeracea sp*	+	+
			Hydropsychidae	*Arctopsyche sp*	+	-
				Hydropsyche betteni	+	+
				Macrostemum sp	+	+
				Parapsyche sp	+	-
			Lepidostomatidae	*Lepidostoma sp*	+	+
			Leptoceridae	*Leptocerus sp*	+	+
				Triaenodes tardus	-	+
			Philopotamidae	*Chimara sp*	+	+
				Dolophilodes sp	+	+
				Philopotamus sp	+	-
		Ephemeroptera	Baetidae	*Acentrella sp*	+	-
				Baetis sp	+	+
			Caenidae	*Caenis sp*	+	+
			Dicercomyzinae	*Dicercomyzon femorale*	+	+
			Heptageniidae	*Ecdyonurus sp*	+	+
			Isonychiidae	*Isonychia sp*	+	+
			Leptophlebiidae	*Adenophlebia auriculata*	+	+
				Adenophlebiodes sp	+	+
				Thraulus bellus	-	+
			Machadorythinae	*Machadorythus palanquim*	+	-
			Polymitarcidae	*Ephoron sp*	+	+
			Tricorythidae	*Tricorythus sp*	-	+
		Coleoptera	Dytiscidae	*Neptosternus sp*	+	+
			Elmidae	*Elmis sp*	+	+
				Pseudomacronychus decoratus	+	+
			Gyrinidae	*Gyretes sp*	+	+
			Hydrophilidae	*Helobata sp*	+	+

				Hydrochara sp	-	+
				Hydrophilus sp	+	-
			Psephenidae	*Psephenus sp*	+	-
			Scirtidae	*Cyphon sp*	+	-
				Elodes sp	+	+
			Staphylinidae	*Euvira sp*	+	-
		Heteroptera	Corixidae	*Corixa sp*	+	-
				Microvelia sp	+	-
			Gerridae	*Gerris sp*	-	+
			Mesoveliidae	*Mesovelia sp*	+	-
			Naucoridae	*Naucoris sp*	-	+
			Pleidae	*Perla sp*	+	+
			Rhagovelinae	*Rhagovelia distincta*	+	+
		Odonata	Calopterygidae	*Calopterix virgo*	+	+
			Chlorocyphidae	*Chlorocypha sp*	+	+
			Corduliinae	*Nehalennia speciosa*	+	-
				Somatochlora metallica metallica	+	+
			Gomphidae	*Gomphus sp*	+	-
				Hagenia sp	+	-
			Libellulidae	*Libellula sp*	-	+
		Diptera	Athericidae	*Atherix sp*	+	+
			Ceratopogonidae	*Bezzia sp*	-	+
			Chironomidae	*Chironomus sp*	+	+
				Polypedilum sp	+	+
			Simuliidae	*Similium venustum*	+	+
			Tipulidae	*Hexatoma spinosa*	+	+
Annelida	Oligocheta	Haplotaxida	Haplotaxidae	*Haplotaxis sp*	+	-
			Lumbricidae	*Eiseniella tetraedra*	+	-
	Mollusca	Mesogasteropoda	Thiaridae	*Melanoides tuberculata*	+	+
				Potadoma freethi	+	+
		Basomatophora	Lynnaeidae	*Stagnicola sp*	-	+
			Physidae	*Physa sp*	+	-
	Planaria	Tricladida	Dugesiidae	*Dugesia lugubris*	+	+
3	5	12	50	*68*	57	48

Note: + Species present; - Species absent

3.6. Diversity Indices

In the Moulé watershed, the Shannon-Weaver diversity index (H') is 3.36 ± 0.75, indicating overall diversity within the community. However, H' varies from one site to another, ranging from 1.36 (LYB01) to 3.74 (MOUL7). In the Zadié watershed, the average H' value is 2.96 ± 0.64, indicating low overall diversity. However, values vary from one site to another, ranging from 1.70 (ZAD01) to 3.63 (BEK01). The average Piélou Evenness value in the Moulé watershed is 0.77 ± 0.12, and in the Zadié watershed, it is 0.74 ± 0.14. These two values reflect a balanced population despite the beginnings of imbalance observed at certain stations, such as LYB01 in the Moulé watershed, where the index value is 0.42 (LYB01), and ZAD01 in the Zadié watershed, where this value is 0.43. The average Simpson's dominance index value is 0.15 ± 0.15 in the Moulé watershed and 0.20 ± 0.16 in the Zadié watershed. These values, still close to zero, indicate the absence of dominant taxa. Table 3 below presents the average value of each index.

Table 3 Mean value and standard deviation of diversity indices in each watershed

	Watershed	
	Moulé	**Zadié**
Shannon Index	3.36±0.75	2.96±0.34
Simpson Index	0.15±0.15	0.20±0.16
Evenness Index	0.77±0.12	0.74±0.14

4. Discussion

Water temperature, oxygen saturation, and pH showed a significant difference ($p<0.05$) between the Moulé and Zadié watersheds. The lowest temperatures (21°–22.5°C) were measured in the Moulé watershed, and the highest (22°–24°C) in the Zadié watershed. This temperature difference is primarily due to the denser canopy in the Moulé watershed compared to the Zadié watershed, which limits the amount of sunlight reaching the undergrowth. Indeed, the use of mechanical equipment, the opening of tracks to facilitate the removal and extraction of ore using high-powered motorized equipment, has led to greater deforestation of the Zadié watershed, resulting in increased sunlight and consequently a rise in water temperature. This observation has been highlighted by several authors [15; 16; 17].

Dissolved oxygen saturation is extremely low in both watersheds, ranging from 8% to 12% in Moulé and from 15% to 25% in Zadié. These levels could be explained by the decomposition of organic matter, which is common in stagnant forest areas. Furthermore, the descriptions in the continuity of watercourses in both watersheds were observed stagnant water often harbors high microbial activity which led a low in situ dissolved oxygen concentrations. The low concentrations of dissolved oxygen are often not beneficial to benthic macroinvertebrate communities [18].

The measured pH values reveal lower alkalinity in the Zadié basin (7.20–7.50 UC) and higher alkalinity in the Moulé basin (7.50–8.25 UC). These values could result from the nature of the terrain traversed by the watercourses of these two hydrosystems [15; 19]. However, these values do not yet endanger the development of aquatic life because they are below 9.5, which is considered lethal [20].

Regarding conductivity and turbidity, the Kruskal-Walli's test ($p>0.05$) showed no significant difference between the waters of the streams in the two watersheds. The low electrical conductivity values recorded, ranging from 30 to 100 µS/cm, indicate low water mineralization, more pronounced in the Zadié basin (25-70 µS/cm) than in the Moulé basin (25-105 µS/cm). Turbidity also exhibited the same spectrum, with lower values in the Zadié basin (15-25 mg/l) and higher values in the Moulé basin. The variation in the values of these two parameters could be explained by increased runoff in the Moulé basin. Authors such as [21] state that water runoff leads to an increase in electrical conductivity and dissolved solids (DSS) levels in river water. These views are consistent with those of [31], who observed a significant increase in conductivity, sediment load, and metals such as manganese.

The results of the physicochemical analysis of the waters of the two catchment areas, as well as those of the Pearson correlations, suggest distinct levels of disturbance and indicate that the two types of gold mining practiced in each catchment generate distinct physicochemical conditions, particularly in terms of thermal regime, oxygenation and acidity of the waters. These results show that gold mining activity in the upper Ivindo region has a measurable but variable impact on the abiotic parameters of the region's waterways. Therefore, gold mining leads to a degradation of water quality as well as a loss of benthic macrofauna.

Compared to other watersheds in Gabon, this biological inventory shows low taxonomic richness. Indeed [24] [30]. In fact, the abundance and species richness of benthic macroinvertebrates, as well as the abundance of sensitive EPT groups (Mayflies, Stoneflies, and Trichoptera), are lower in exploited rivers. Our results corroborate those of [32] and many other authors where low levels of taxonomic richness, resulting from the direct discharge of wastewater into watercourses, have been highlighted in anthropized hydrosystems [25], [26] and in the DRC [23]. In the context of this inventory, the low taxonomic richness recorded is likely due to the disruption of the river continuum, increased turbidity, and sediment deposits, which have probably led to the suffocation of microhabitats and biota. In the Zadié basin, the significant accumulation of sediment has transformed the river channel into a large, shallow fishpond, completely altering the available ecological niches and resulting in a loss of protection against predators and a decline in food quality.

Despite these underlying problems, the Arthropoda phylum and the Insecta class represent 96.83% of the population at Zadié and 96.45% in Moulé, and no significant difference in the diversity of benthic macroinvertebrate populations was detected between the two watersheds, although the Moulé basin has a higher taxonomic richness and abundance than Zadié, suggesting a differential impact of the two exploitation methods on benthic communities. Concurrently, the Ephemeroptera-Plecoptera and Trichoptera (EPT) group represents 63% of the population size in both watersheds, indicating that the biological quality of the waters is still good and therefore that the ecological integrity is fairly good. This percentage of EPT shows that there is not yet significant organic pollution in these two watersheds. The preponderance of Arthropods over other taxonomic groups, their abundance and diversity are very often associated in many studies of benthic macroinvertebrate populations as indicators of a low human impact on aquatic communities [15], [22], [23], [24].

The Shannon-Weaver index (H') value is high across all stations in both watersheds, fluctuating between 2.96 and 3.36. Only 3 out of 16 stations have an H' value below 3: ZAD01 (H'=1.80) and OMI01 (H'=2.5) in the Zadié watershed, and station LYB01 (H'=1.5) in the Moulé watershed. The high H' values in 81% of the stations in both watersheds indicate good biodiversity and ecological health; the Piélou evenness index values confirm a balanced state of the stands with an absence of dominant taxa. Similar values for the H' and Evenness indices have been obtained by several authors in areas little or not disturbed by human activities [27], [28], and [29]. This means that gold mining activity has had a low direct impact on the benthic macroinvertebrate communities of the sites and therefore of the watersheds, as many authors have extensively supported the fact that low species diversity and low abundance are generally explained by human activities [15], [22].

Indeed, the high specific diversity and abundance of benthic macroinvertebrates in both watersheds show that the impact of the use of industrial machinery (excavators, trucks, industrial pumps) versus rudimentary means (low-power motor pump, pack saddle, ordinary shovel, pickaxe) used by small operators called gold panners has a limited direct ecological impact in the short term on the populations of benthic macroinvertebrates.

5. Conclusion

In analyzing the results of this inventory, we measured the impact of using industrial machinery versus rudimentary tools in gold mining activities in two sub-basins of the Ivindo River. The results show a fairly similar taxonomic richness, and in both sub-watersheds, the Arthropoda phylum, particularly the class Insecta, represents 96.83% of the population at Zadié and 96.45% at Moulé. The diversity indices indicate diverse and balanced populations at the stations in both sub-watersheds. These results show that the two gold mining methods generate distinct physicochemical conditions likely to influence the ecological dynamics of the watercourses. The high proportion of pollution-sensitive taxa and the high values of the diversity indices suggest that biological integrity is still largely preserved. In the short term, the direct impact on benthic communities remains limited, although some metrics indicate a trend toward ecological differentiation between basins. These results constitute an essential baseline for the long-term ecological monitoring of tropical forest hydrosystems subjected to gold mining.

Compliance with ethical standards

Acknowledgments

The authors would like to thank Global Mine Development for funding this survey, and its geological engineers Nkogho Mfolé, Alain Giresse and Thomas Feki Edjamina for their participation in the fieldwork.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Tixier Guillaume. 2004. L'acidification anthropique des eaux de surface Effets sur les communautés de macro invertébrés benthiques Autoécologie et réponses d'espèces caractéristiques des ruisseaux de tête de bassin des Vosges. Thèse de Doctorat de l'Université de Metz. 256 p.

[2] United States Environmental Protection Agency (U.S. EPA). 2002. Biological Assessments and Criteria: Crucial Components of Water Quality Programs. United States Environmental Protection, Agency, EPA822-F-02 006. http://www.epa.gov/ost/biocriteria/ technical/brochure.pdf.

[3] American Public Health Association, American Water Work Association, Water Environment Federation, Standard methods for examination of water and wastewater, 23rd ed. American Public Health Association, 800 I Street NW, Washington, DC 20001-3710, 2017.

[4] Rodier J., Legube B., Merlet N., and Coll, L'analyse de l'eau : Eaux naturelles, eaux résiduaires, eaux de mer. 9éme édition, Dunod, Paris, 1526p 2009.

[5] Durand, J.R. et Levêque C., 1981. Flore et Faune Aquatiques de l'Afrique Sahélo-Soudanienne, Tome 1 et Tome II. ORSTOM. France, 873 p

[6] Heidemann H. et Seidenbusch R., 2002. Larves et exuvies des libellules de France et d'Allemagne. 371 p.

[7] Bilardo A. et Rocchi S., 2010. Haliplidae, Noteridae, Dytiscidae (Coleoptera) du Gabon (7ème partie). Parc National des Plateaux Batéké (mission 2007 et 2008) et considérations sur qualques espèces du genre Neptosternus Sharp, 1882 en Afrique Centrale. Atti Soc.it.Sci. nat. Museo civ. Stor. Nat. Milano, 151 (I): 11-50, Gennaio.

[8] Merritt R.W., Cumming K.W. et Berg M.B., 2008. An introduction to the Aquatic insects of North America. Ed. Kendall Hunt.

[9] Moisan J., 2008. Année inconnue. Photo d'accompagnement au guide d'identification des principaux macroinvertébrés d'eau douce du Canada. 67 p

[10] Tachet H., Bournaud M. et Usseglio-Polatera P., 2010. Invertébrés d'eau douce : systématique, biologie, écologie. Edition CNRS, Paris. 581 p

[11] Shannon, C. E. and Weaver, W. (1963). The Mathematical Theory of Communication. University of Illinois Press (cf. p. 44, 57).

[12] Pielou, E. C. 1966. The measurement of diversity in different types of biological collections. Journal of Theoretical Biology 13 : 131–144.

[13] Leroy, T., 2006. Evolution du peuplement d'Odonates adultes au cours d'une saison sur les rives d'un lac-tourbière d'Auvergne (France). Martinia, 22 (3) septembre 2006, 109-118.

[14] Grall J. et Coïc N., 2005. Synthèse des méthodes d'évaluation de la qualité du benthos en milieu cotier. 80 p.

[15] Wilfreid Christiane Noel Betsi, Samuel Foto Menbohan, Nathaniel Larry Lactio, Yvonne Laure Tchouapi, Marie Anita Zemo Temgoua, Donald L'or Nyame Mbia, Serge Roger Gwos Nhiomock, Mathias Nwaha, Eric Belmond Biram A Ngon, Jean Dzavi, Blaise Rollinat Mboye and Moïse Nola. 2023. Comparative approach of the fauna diversity of benthic macroinvertebrates in a stream on ferralitic soil and equatorial climate at 2 seasons in Cameroon (Central Africa). World Journal of Advanced Research and Reviews, 19(01), 254–264.

[16] Liechti P., Frutiger A., and Zobrist J. 2004. Methods of analysis and assessment of Swiss watercourses. Module chimie, analyses physico-chimiques niveaux R and C. SAEFL Bern, 11-12p.

[17] Nyamsi Tchatcho N.L. 2018. Benthic macroinvertebrates of the Mefou river system: habitat, diversity and population dynamics, assessment of the biological integrity of the watercourses. Doctoral thesis/Ph.D in Biology of Animal Organisms, University of Yaoundé 1, 159p.

[18] Belhaouari B., Rouane-Hacene O., Bendaha M. 2014. Effects of Metal Sulfates on Catalase and Glutathione-S transferase of Marine Gastropoda: Osilinus turbinatus. Journal of Applied Environmental and Biological Sciences, 4 (9): 191-196.

[19] Rodier J., Legube B., Merlet N. 2009. L'analyse de l'eau. Paris, Dunod, 9e édition, 1579 p.

[20] MEDD. 2003. Système d'évaluation de la qualité des cours d'eau, éd. Ministère de l'Environnement, de l'Energie et de la Mer (France). 40 p.

[21] Camara A.I, Diomande D. and Gourene G. 2014. Impact des eaux usées et de ruissellement sur la biodiversité des macroinvertébrés de la rivière banco (parc national du banco ; Côte d'Ivoire), REV. CAMES, Vol. 02.

[22] Michael Baraka Nyakabeji, Éric Mihingano Mushagalusa, Jean-Jacques Mashimango Bagalwa et Augustin Kanyunyi Basabose. 2023. Diversité des macroinvertébrés benthiques des rivières du nord-est de l'île d'Idjwi, République Démocratique du Congo. VertigO - la revue électronique en sciences de l'environnement

[23] Dieudonné Zizirane, Jean Jacques Bangalwa, M. Isumbisho, M. Mulengezi, I. Mukumba, M. Bora, J.M. Mucheso, A. Lukamba, G. Iragi, B. Irenge, F. Kibangu et R. Kamangala. 2023. Évaluation comparée de la pollution des rivières Kahuwa et Mpungwe par l'utilisation des macroinvertébrés benthiques. VertigO - la revue électronique en sciences de l'environnement. Volume 14, Numéro3.

[24] Blaise Rollinat MBOYE, Samuel FOTO MENBOHAN, Jean Daniel MBEGA, Eric Belmond BIRAM à NGON. 2018. Influence of the Granulometric parameters on the Diversity and Distribution of Benthic Macroinvertebrates in the Mabounié Watershed (Central West Gabon). Int. J. Adv. Res. Biol. Sci. 5(7): 252-270.

[25] Foto M.S., Zébazé T.S.H., Nyamsi T.N.L., Ajeagah G.A., Njiné T. 2011. Evolution Spatiale de la diversité des Peuplements de Macroinvertébrés Benthiques dans un cours d'eau Anthropisé en Milieu Tropical (Cameroun). European Journal of Scientific Research, n° 55, pp. 291-300.

[26] Tchakonté S. 2016. Diversité et structure des peuplements de macroinvertébrés benthiques des cours d'eau urbains et périurbains de Douala (Cameroun). Thèse de Doctorat/PhD. Université de Yaoundé, 205p.

[27] Ngameni Tchamadeu Norbert, Asanga Patricia Fai, Mpoame Mbida et Kenko NKontcheu Daniel Brice. 2017. Impact De L'exploitation Artisanale De La Sabliere De Toutsang Sur La Structure Des Communautes De Macroinvertebres Du Cours D'eau Doulahang A Dschang (Ouest Cameroun). European Scientific Journal Vol.13, No.23 ISSN : 1857 – 7881.

[28] Onana F.M., Zébazé T.S.H., Koji E., Nyamsi T.N.L. et Tchakonté S. 2016. Influence of municipal and industrial pollution on the diversity and the structure of benthic macro-invertebrates' community of an urban river in Douala, Cameroon. Journal of Biodiversity and Environmental Sciences (JBES), n° 8, pp.120-133.

[29] Tshijik J-C. K., Akaibe D., Micha J-C. et Pwema V.K. 2016. Analyse comparative de la diversité taxonomique et de la qualité écologique de l'eau des rivières Lukunga et Mangengenge à Kinshasa. International Journal of Innovation and Applied Studies, n°16 : 260-271.

[30] Blaise Rollinat MBOYE, Aubin Armel KOUMBA, Jean DZAVI, Ghislain TCHINGA, Samuel FOTO MENBOHAN et Jean Daniel MBEGA. 2020. Abondance, diversité et valeur indicatrice des macroinvertébrés benthiques des cours d'eau forestier du bassin versant de la Mabounié au Gabon. Afrique SCIENCE 17(1) 89 – 103

[31] Karunia Macdonald, Mark Lund and Melanie Blanchette. 2015. Impacts of Artisanal Small-Scale Gold Mining on Water Quality of a Tropical River (Surow River, Ghana). 10th International conference on acid rock drainageandIMWA annual conference. Mine Water and Environment Research Centre, Edith Cowan University, Australia. 12 p.

[32] Patteson Mwagona Chula, Evariste Rutebuka and Paul Luis Schmidt Yáñez. 2013. The effect of illegal small-scale gold mining on stream macro-invertebrate assemblages in the East Usambara Mountains.