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Research Paper

Macroinvertebrates Assemblages as Bioindicators of Ecological Health in Lake Arekit: Response to Physicochemical Stressors in a Tropical Highland Lake

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Abstract

Freshwater lakes in tropical highlands face growing threats from human activities, but their ecological responses are poorly understood. This study examines the spatial distribution of benthic macroinvertebrates in Lake Arekit, Ethiopia, and their relationship with water quality to assess ecological health under agricultural and urban pressures. Water quality and macroinvertebrate communities were analyzed at three sites from February to May 2023. Results showed significant spatial differences in water quality ($p < 0.05$), with higher turbidity (110.11 NTU), nitrate (36.37 µg L^{-1}), and ammonium (83.95 µg L^{-1}) at disturbed sites. Macroinvertebrate communities included six taxa, dominated by pollution-tolerant Chironomidae (22.4%), Odonata (31.5%), and Hemiptera (29.6%), with low diversity (Shannon index: 1.3–1.5) indicating moderate pollution. Redundancy Analysis (RDA) linked ammonium (NH_3-N), turbidity, and total dissolved solids to community structure, explaining 93.2% of species-environment variance. The shoreline site, affeced by waste and runoff, had fewer taxa (5) and more tolerant species, while the macrophyte site had higher diversity (6 taxa). These findings reveal Lake Arekit's ecological decline and highlight macroinvertebrates as effective bioindicators. Recommendations include reducing fertilizer use and improving wastewater treatment to combat eutrophication and protect biodiversity. This study offers a monitoring framework for freshwater ecosystems in developing regions facing similar human-induced threats.

1. Introduction

Aquatic ecosystems represent intricate networks of dynamic interactions between biological communities and their physicochemical surroundings, collectively shaping biodiversity and ecosystem processes (Bănăduc et al., 2024; Daam et al., 2019). Within these systems, macroinvertebrates serve critical functions as bioindicators of environmental quality, facilitators of nutrient cycling, and keystone organisms within aquatic food webs (Liu et al., 2023; Zhou et al., 2024). The spatial distribution and taxonomic diversity of these organisms are strongly governed by physicochemical parameters, including temperature regimes, dissolved oxygen levels, pH, nutrient availability, and water clarity (Chi et al., 2024). Elucidating these linkages is essential for evaluating ecosystem integrity, especially in lentic environments such as lakes, which face escalating threats from anthropogenic disturbances, including pollution, eutrophication, and climate change impacts.

Lakes, as enclosed aquatic systems, serve as sentinels of environmental change by integrating catchment-level influences into their physicochemical dynamics (Wondmagegn & Mengistou, 2023). These parameters define microhabitat conditions that either promote or restrict macroinvertebrate communities, mirroring the broader ecological state of the system (Abnet & Seyoum, 2020; Wondmagegn & Mengistou, 2020, 2023). For example, hypoxic conditions (low dissolved oxygen) often exclude pollution-sensitive taxa, whereas excessive phosphorus loading can trigger algal proliferation, destabilizing benthic habitats (Mao et al., 2023; Zhou et al., 2024). Although prior research underscores the value of macroinvertebrates in biomonitoring (Abnet & Seyoum, 2020; Liu et al., 2023; Wondmagegn & Mengistou, 2023), significant gaps persist in understanding how these relationships vary across heterogeneous lake ecosystems, especially under compounding anthropogenic stressors.

This study explores the spatial distribution of macroinvertebrates in Lake Arekit, a freshwater system confronting emerging pressures from agricultural runoff and urban expansion (Tilahun et al., 2022; Enawgaw & Wagaw, 2023), in relation to critical physicochemical variables. By evaluating correlations between these variables (e.g., nutrient levels, dissolved oxygen) and macroinvertebrate community composition, this work seeks to identify the mechanistic drivers underlying biodiversity patterns. The results will improve predictive frameworks for ecosystem management and yield actionable insights to safeguard lake health amid rapid environmental shifts. By integrating ecological theory with conservation practice, this research advances a template for sustainable freshwater management in anthropogenically altered aquatic ecosystems.

2. Materials and Methods

2.1. Study Area Description

Lake Arekit (approximately 37°53′30″ to 38°10′00″ E and 7°59′30″ to 8°16′00″ N; Fig. 1) is a freshwater system situated in the Gurage Zone, Ethiopia, at an elevation ranging from 2,820 to 2,950 meters above sea level. The lake covers a surface area of 130 hectares, with a maximum depth of 1.5 meters, and receives its hydrologic input primarily from groundwater discharge and seasonal rainfall (Enawgaw & Wagaw, 2023). Its catchment area is characterized by mixed agricultural land use, dominated by smallholder farms cultivating *Eucalyptus* spp., apple, potato, and coffee, alongside peri-urban settlements experiencing rapid infrastructural expansion (Tilahun et al., 2022; Enawgaw & Wagaw, 2023).

The lake's physicochemical dynamics are strongly seasonal, with pronounced wet (June–September) and dry (December–February) phases driving fluctuations in water levels, nutrient loading, and turbidity. Intensified agricultural runoff particularly nitrogen and phosphorus from fertilizers and untreated urban wastewater discharge has been identified as a growing threat, exacerbating eutrophication and habitat fragmentation (Enawgaw & Wagaw, 2023). Ecologically, Lake Arekit sustains diverse biological communities, including wetland birds (Tilahun et al., 2022), phytoplankton, zooplankton (Enawgaw & Wagaw, 2023; Enawgaw et al., 2023), and fish species such as *Cyprinus carpio* and *Oreochromis niloticus* (Wagaw et al., 2024), which play vital roles in nutrient cycling and trophic interactions.

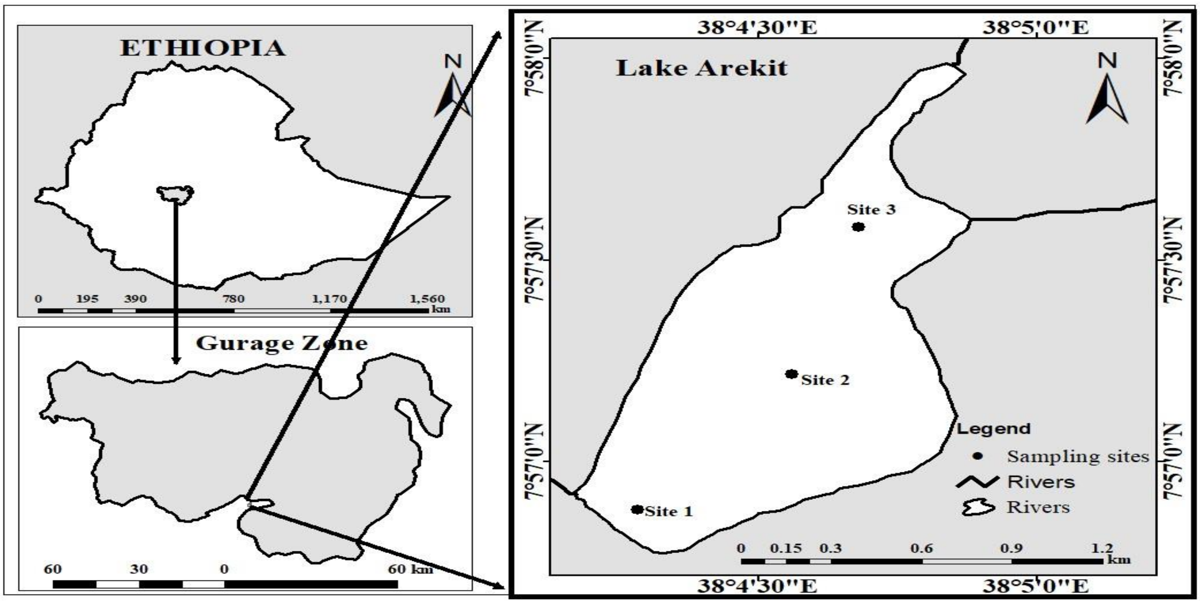

Figure 1: Map showing the study area and sampling locations

2.2. Sampling Points

Three data collection points (sampling sites) were selected across Lake Arekit, representing different habitat types within the lake. The sites were chosen based on spatial distribution to capture variations in nutrient levels, depth, and substrate types (mud, sand, and vegetation). The three predetermined sites were referred to as shoreline area (site 1), open-water area (site 2), and macrophyte coverage area (site 3). Site 1 is found in the main gate of the lake and it was more altered by human pressures; it is labeled as highly impaired. Site 2 is located in the open area of the lake. This site was relatively less affected by human activity and was thought to be moderately impaired. Site 3 was found in the eastern corner of the lake and the site had relatively good macrophyte coverage and is considered to be a reference site (Table 1).

Table 1: Location of collection points and their characteristics

Sampling points	GPS location	Descriptions of sampling sites
Point -1 (Shoreline Area)	Hight:2878 m Latitude: 7° 56' 53.38" N Longitude: 38° 4' 11.28" E	This site, located along the main entrance road to Lake Arekit, shows significant shoreline modification. As the lake's primary fish landing area, it hosts activities such as car washing, swimming, cattle grazing, and waste disposal from the town, making it highly impaired.
Point -2 (Open-Water Area)	Height: 2882 m Latitude: 07° 25' 27" E Longitude: 38° 3' 42.91" E	Located in the middle of the lake's open water, this site is somehow far from anthropogenic drivers and is moderately impaired.
Point -3 (Macrophyte Area)	Height: 2882 m Latitude: 07° 57' 31.32" E Longitude: 38° 3' 37.76" E	This site shows evidence of natural habitats and macrophyte cover, making it minimally impaired. It is relatively less affected and is regarded as a benchmark site-reference site.

2.3. Sampling

2.3.1. Macroinvertebrate Sampling

Benthic macroinvertebrates were collected from February to May 2023 at three selected sites. At nearshore sites, three transects were established extending from the water's edge to a depth of 0.7 meters. Macroinvertebrates were sampled along these transects using a D-frame traveling kick net (30 cm × 28 cm, 500 µm mesh), with each deployment lasting 10 minutes to ensure standardized collection (Jones et al., 2004). These three net samples were then combined into a single composite sample for each site. At open water sites, triplicate quantitative samples were collected using an Ekman grab (225 cm^2 sampling area), and these three grab samples were similarly pooled into one composite sample per site. All samples were fixed in 70% ethanol and stored at the Wolkite University Biology laboratory until analysis.

Taxonomic identification at the family level was performed using standard keys (Bouchard, 2004; Mbogho & Sites, 2013; Oscoz, Galicia, & Miranda, 2011)). Ecosystem diversity was assessed using several indices, including species richness (S), the Shannon diversity index (H'), Pielou's evenness (J), and Simpson's dominance index (D) (Pinto-Coelho et al., 2008).

2.3.2. Physicochemical variables sampling and analysis

At each macroinvertebrate sampling site, several physical parameters of the lake water—pH, temperature (°C), conductivity (µS/cm), total dissolved solids (TDS, mg/L), and dissolved oxygen concentration (mg/L) were measured in situ using a portable HACH HQ9012 multiparameter probe. Water samples were also collected at each site for nutrient analysis. Nitrate was determined using the sodium salicylate method, ammonium by the indophenol blue method (APHA, 1995), silica by the molybdosilicate method, and both soluble reactive phosphate and total phosphate by the ascorbic acid method (APHA, 1999). Nitrite concentrations were measured using the sulfanilamide and N-naphthyl-(1) ethylenediamine-dihydrochloride reaction (APHA, 1995).

2.4. Data Analysis

Data were managed using SPSS 20.0 (Ho, 2013). Analysis of variance (ANOVA) was used to test for significant differences in physicochemical parameters among the three sampling sites. The relationship between benthic macroinvertebrate taxa distribution and physicochemical variables was explored using canonical multivariate analysis in CANOCO 4.5 (Ter Braak & Smilauer, 2002). A detrended correspondence analysis (DCA) revealed a gradient length of 1.52, indicating a linear response of the macroinvertebrate data to environmental variables; therefore, redundancy analysis (RDA) was employed. Taxa with a total abundance of less than 0.1% were excluded from this analysis. The Shannon-Wiener diversity index, dominance, and evenness were calculated using PAST software. Kruskal-Wallis tests were used to determine significant differences in diversity indices and invertebrate abundance among sites.

3. Results

3.1. Physicochemical variables

The physicochemical properties of Lake Arekit varied significantly across sampling sites ($p < 0.05$), with the exception of total phosphorus (TP) (Table 2). Water temperature ranged from 19.1°C to 20.8°C, averaging 20.12 ± 0.88°C, and showed significant spatial variation ($p < 0.05$). Dissolved oxygen (DO) levels were significantly different among sites ($p < 0.05$), with notably higher concentrations at both macrophyte (11.74 mg L^{-1}) and shore (11.37 mg L^{-1}) sites compared to open water. The lake was alkaline, with pH values ranging from 10.35 to 10.78 and exhibiting significant spatial variation ($p < 0.05$).

Electrical conductivity (EC) ranged from 68.34 µS cm^{-1} to 71.64 µS cm^{-1}. Turbidity was highest at the shore (110.11 NTU), while open water and macrophyte sites had similar, statistically significant ($p < 0.05$) values. Total dissolved solids (TDS) and turbidity, also measured, showed spatial variation ($p < 0.05$), with the highest values observed at the shore (44.33 mg L^{-1} and 110.11 NTU, respectively).

Nutrient analysis revealed variations in inorganic nitrogen and phosphorus concentrations. Nitrate-nitrogen (NO_3-N) was significantly higher at the shore (36.37 µg L^{-1}), while ammonium-nitrogen (NH_3-N) was significantly higher at the macrophyte site (83.95 µg L^{-1}) ($p < 0.05$) (Table 2). Total phosphorus (TP) concentrations did not vary significantly among sites. Soluble reactive phosphorus (SRP) and silica (SiO_2) concentrations varied significantly across sampling sites ($p < 0.05$), with the highest SRP concentration recorded in open water (13.47 µg L^{-1}) and the highest silica concentration at the macrophyte site (7.11 µg L^{-1}).

Table 2: Spatial variations among sampling sites of selected physicochemical variables in Lake Arekit

	Sampling sites			
Physicochemical variables	**Open**	**Macrophyte**	**Shore**	**Mean± SD.**
Temp (^{0}C)	19.1±0.49^a	20.8±0.23^b	20.47±0.49^b	20.12±0.88
DO(mg L^{-1})	8.9±0.42^a	11.74±0.31^b	11.37±0.53^b	10.67±1.35
pH	10.35±0.48^a	10.78±0.11^b	10.58±0.19^{ab}	10.57±0.34
Turb.(NTU)	84.14±2.84^a	84.08±1.21^a	110.11±5.23^b	92.78±12.94
TDS	42.33±1.32^{ab}	41.34±2.93^a	44.33±2.35^b	42.67±2.54
EC(mS cm^{-1})	68.34±0.35^a	71.11±0.72^b	71.64±0.77^b	70.36±1.60
Inorganic nutrients				
NO_3-N (µgL^{-1})	3.91±2.18^a	22.48±8.12^b	36.37±6.08^b	20.92±15.03
NH_3-N(µgL^{-1})	78.24±3.30^a	83.95±0.83^b	73±1.43^b	78.40±5.09
TP -P (µgL^{-1})	196.13±9.45^a	197.47±11.02^a	196.13±9.45^a	196.58±8.69
SRP-P (µgL^{-1})	13.47±4.16^a	5.47±1.15^b	4.27±0.92^b	7.73±4.86
SiO_2-Si (mg L^{-1})	5.91±0.17^a	7.11±0.03^b	7.08±0.29^b	6.7±0.61

Note. Means within a row with different letters (a, b) are significantly different (Tukey test, $p < 0.05$) (Temp: temperature; DO: dissolved oxygen; Turb: turbidity; EC: electrical conductivity)

3.2. Abundance and Diversity of Benthic Macroinvertebrates

Six macroinvertebrate taxa, representing five orders, were identified in Lake Arekit (Table 3). Order Hemiptera was represented by the most families (two), while each of the other orders contained only one family (Table 3). The lowest taxa richness (five taxa) was observed at the Shore site, while the Open and Macrophyte sites each had the highest richness (six taxa). Taxa richness did not differ significantly among the studied sites ($p > 0.05$). Mean macroinvertebrate abundance varied considerably, ranging from 332 ind. m^{-2} at the Shore site to 1807 ind. m^{-2} at the Macrophyte site, with significant variation observed among sites ($p < 0.05$) (Table 3, Fig. 2). Odonata dominated the benthic macroinvertebrate community in Lake Arekit, accounting for 31.5% of total abundance, followed by Hemiptera (29.6%) and Diptera (22.4%). Other groups, including Hirudinae (10.1%) and Ephemeroptera (6.4%), represented smaller proportions of the assemblage (Table 3). Shannon diversity index values ranged from 1.3

at the Open site to 1.5 at the Macrophyte site, but these differences were not statistically significant ($p > 0.05$) (Fig. 3). Equitability, however, varied significantly across sites ($p < 0.05$), ranging from 0.73 at the Open site to 0.93 at the Shore site. Similarly, Pielou's evenness index showed significant variation among sites ($p < 0.05$), ranging from 0.61 at the Open site to 0.89 at the Shore site. The Shore site exhibited a significantly higher evenness value (0.89) than both the Macrophyte (0.71) and Open (0.61) sites, which were not significantly different from each other (Fig. 2).

Table 3: Distribution of macro-invertebrate families at each study site (+ = Present and - =Absent)

Order/Class	**Family**	**Sites**				**Relative**
		Shore	**Open**	**Macrophyte**	**Number**	**Abundance (%)**
Ephemeroptera	Baetidae	+	+	+	384	6.4
Odonata	Coenagrionidae	+	+	+	1877	31.5
Hemiptera	Gerridae	+	-	+	207	3.5
	Notonectidae	+	+	+	1558	26.1
Diptera	Chironomidae	+	+	+	1336	22.4
Hirudinae	Hirudinidae	+	+	+	604	10.1
Taxa_S		6	5	6		
					Total = 5966	

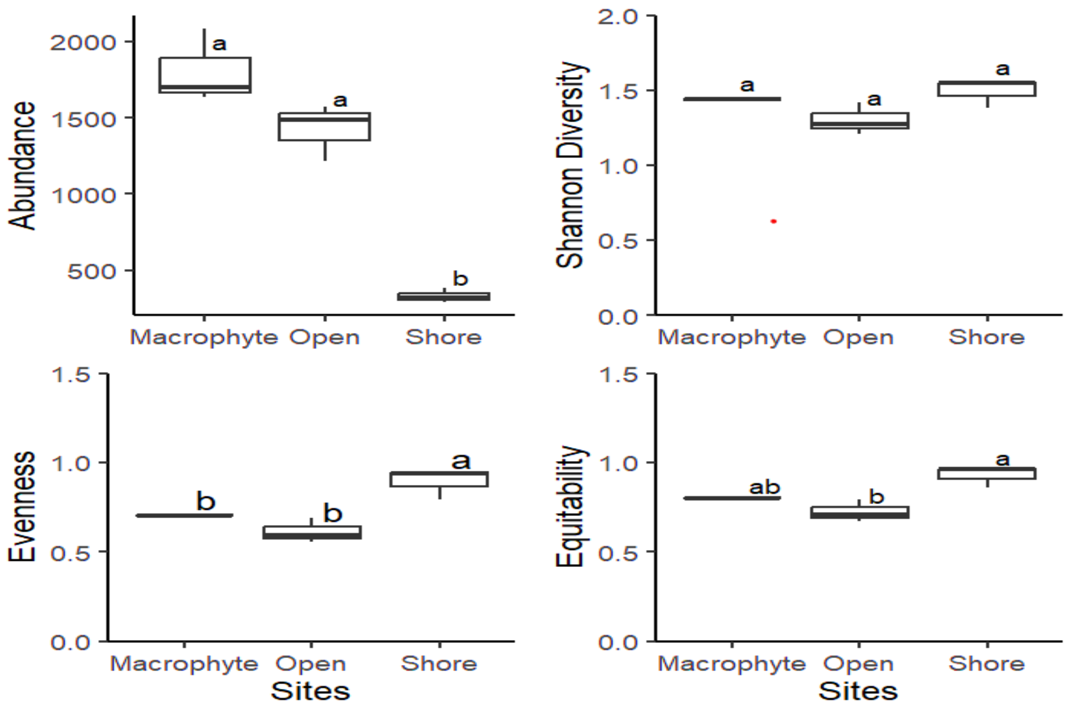

Figure 2: Spatial variation in macro-invertebrate community biodiversity among sampling sites in Lake Arekit

3.3. Correlations of Macro-invertebrates with Physicochemical Variables (RDA Analysis)

The Redundancy Analysis (RDA) plot elucidates the relationships between environmental variables and macroinvertebrate community composition in Lake Arekit (Fig. 3). The RDA results indicate that the first two axes explain 93.2% of the species-environment relationship, with the first axis alone accounting for 68.1% of this variation (Table 4). The remaining 6.8% may be explained by unmeasured physical or biological variables. Ammonium (NH_3-N) and Total Phosphorus (TP) showed strong negative correlations with the first principal component axis, whereas Turbidity (Turb) and Total Dissolved Solids (TDS) exhibited strong positive correlations. The second principal component axis was primarily influenced by Temperature, Dissolved Oxygen (DO), pH, Electrical Conductivity (EC), Nitrate, TP, and SiO_2, which showed strong negative correlations. Soluble Reactive Phosphorus (SRP) had a strong positive correlation with this axis. These variables influence the distribution and abundance of Baetidae (Fig. 3, Table 4). Chironomidae, Gerridae, Coenagrionidae, and Hirudinidae cluster on the left side of the plot, indicating an affinity for higher ammonia nitrogen (NH_3-N) and total phosphorus (TP) in macrophyte-dominated sites, and potentially warmer temperatures and higher pH. Notonectidae, located in the lower left quadrant, suggests a preference for higher pH and temperature, but potentially lower dissolved oxygen (DO) and electrical conductivity (EC). The distribution of samples along these axes reflects variations in community structure related to the measured environmental gradients.

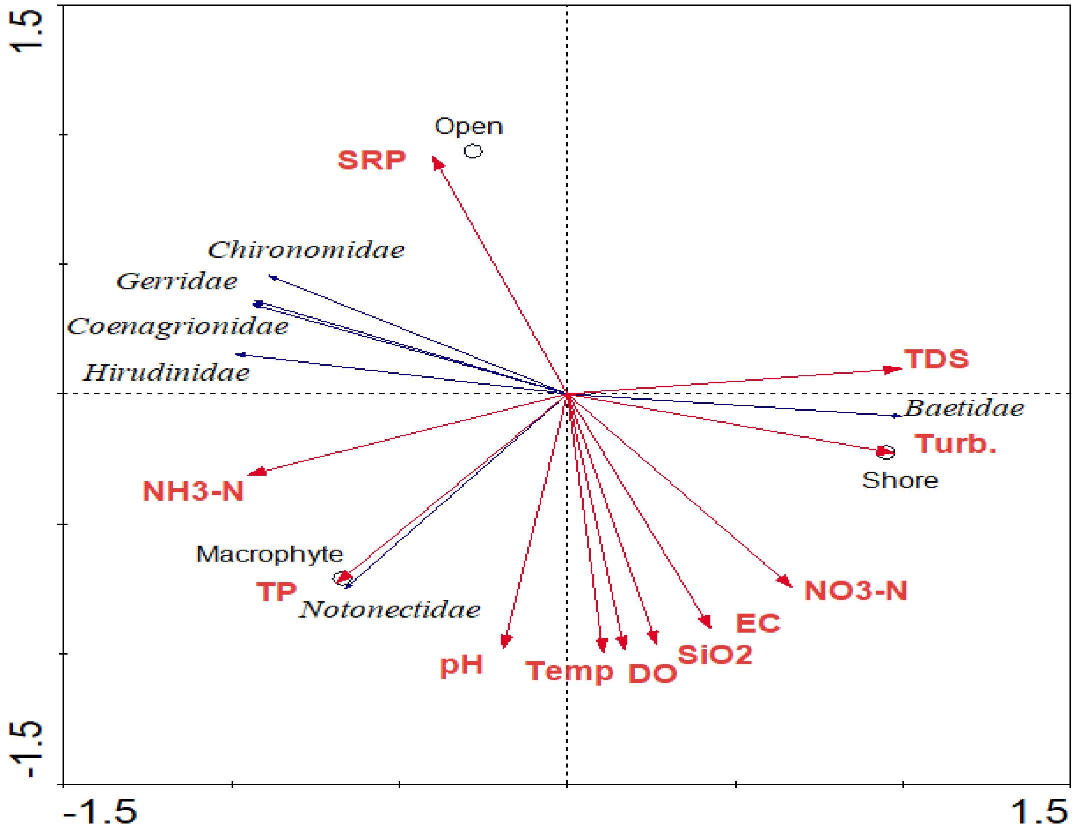

Figure 3: Tri-plot Redundancy analysis (RDA) diagram of macroinvertebrates in relation to water physicochemical properties and sites in Lake Arekit (Macroinvertebrates taxa (blue arrows), physicochemical parameter (red arrows) and Site (Hol Dot), SRP: Soluble Reactive Phosphate; TDS: Total Dissolved Solids; Turb.: Turbidity; EC: Electrical Conductivity; DO: Dissolved Oxygen; Temp: Temperature; TP: Total Phosphorus).

Table 4: Correlation table of physicochemical parameters with the first two axes (significant correlations at p < 0.05 are in bold)

Environmental Variables	Axis-1	Axis-2
Eigenvalues	0.68	0.32
Cumulative percentage variance of species-environment relation	68.1	93.2
Temperature	0.11	-0.99
Dissolved Oxygen (DO)	0.17	-0.99
pH	-0.19	-0.98
Turbidity (Turb)	0.97	-0.23
Total Disssoleved Solids (TDS)	0.99	0.09
Electrical Conductivity (EC)	0.43	-0.90
Nitrate (NO_3-N)	0.67	-0.74
Ammonium (NH3-N)	-0.95	-0.31
Total Phosphorous (TP)	-0.69	-0.73
Soluble Reactive Phosphate (SRP)	-0.40	0.92
Silicon dioxide (SiO_2)	0.27	-0.96

4. Discussion

4.1. Physicochemical Characteristics of Lake Arekit

Water quality parameters in Lake Arekit's sampling sites varied significantly, with the exception of total phosphorus (Table 2). Temperature, dissolved oxygen (DO), pH, electrical conductivity, turbidity, and total dissolved solids all exhibited significant spatial variation ($p < 0.05$). Consistent with these findings, previous studies have documented significant spatial variation in physicochemical variables in other Ethiopian lakes, including Lake Tana (Gezie et al., 2017), Lake Hawassa (Wondmagegn & Mengistou, 2020), Lake Ziway (Woldesenbet & Mengistou, 2020), Lake Ziway (Woldesenbet & Mengistou, 2018), and Lake Shala (Wagaw et al., 2021). These spatial variations likely result from site-specific environmental stressors, habitat heterogeneity, land use patterns, and effluent discharges.

Dissolved oxygen (DO) concentration (mg L^{-1}) was monitored throughout the study period, as it is a direct indicator of an aquatic resource's capacity to support macroinvertebrates and other aquatic life. Low DO levels can alter aquatic communities through direct mortality and reduced population growth of sensitive species. In this study, mean DO levels were 10.67 mg L^{-1}, with significant spatial variation observed among sites ($p < 0.05$). Notably higher concentrations were measured at both the macrophyte (11.74 mg L^{-1}) and shore (11.37 mg L^{-1}) sites compared to the open water site. This variation may be attributed to differences in microbial activity, temperature, organic matter levels, anthropogenic influences, hydrology, macrophyte coverage, and sampling time. These findings are consistent with those of Woldeab et al. (2018), Lencha et al. (2021), and Tibebe et al. (2022), who also reported spatial variations in DO in Ethiopian lakes, attributing them to lake-specific factors such as pollution, land use, and hydrology.

The pH of Lake Arekit ranged from 10.35 to 10.78 (Table 2), classifying the lake ecosystem as alkaline and demonstrating significant spatial variation ($p < 0.05$). The mean pH of 10.57 observed in this study is comparable to values reported for other Ethiopian Rift Valley lakes (Ayenew & Legesse, 2007; Ogato & Kifle, 2017; Wagaw et al., 2021) and Ethiopian highland lakes, including Lake Ardibo (Mohammed et al., 2024) and Lake Hayq (Fetahi et al., 2014;

Tessema et al., 2024). The alkaline pH range of Lake Arekit's water samples is consistent with the characteristics of eutrophic and mesotrophic water bodies (Wagaw et al., 2023). This alkaline nature of Lake Arekit is likely attributable to high concentrations of carbonate salts (e.g., sodium carbonate), the release of alkalis from soluble solutes through chemical weathering and the presence of sodium chloride (Ayenew & Legesse, 2007), and biological activity (Ogato & Kifle, 2017).

Electrical conductivity in this study ranged from 68.34 µS/cm at the open water site to 71.64 µS/cm at the shore site (Table 2), exhibiting significant spatial variation ($p < 0.05$). The higher conductivity observed at the shore site may be attributed to several factors, including potential pollution from municipal waste, agricultural runoff, catchment degradation, multiple stressors around the lake, and reduced water levels. These factors likely contribute to increased ion concentrations at the shore. The mean conductivity value of 70.36 µS cm^{-1} found in this study is similar to the range of 70–110 µS cm^{-1} reported by Ambelu et al. (2013). However, it is considerably lower than the conductivity values reported for other Ethiopian lakes, such as Lake Ziway (489.8 µS cm^{-1}; Woldesenbet & Mengistou, 2018), Lake Ardibo (704.3 µS cm^{-1}; Mohammed et al., 2024), and Lake Hayq (920 µS cm^{-1}; Tessema et al., 2024). These differences likely reflect variations in the geological characteristics of the respective watersheds.

4.2. Inorganic Nutrients

Nutrient analysis revealed significant spatial variations in nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_3-N) concentrations (p < 0.05) (Table 2). The mean nitrate concentration in Lake Arekit (20.92 µg L^{-1}) was considerably higher than that reported for Lake Wonchi (4.72 µg L^{-1}) by Degefu & Schagerl (2015), but lower than values reported for Lake Hayq (167.76 µg L^{-1}; Tessema et al., 2024) and Lake Ardibo (36.53 µg L^{-1}; Mohammed et al., 2024). The highest nitrate-nitrogen concentration (36.37 µg L^{-1}) was observed at the shore site, a finding consistent with observations in Lake Hayq (Fetahi et al., 2014) and Lake Tana (Tibebe et al., 2019). Direct discharges and surface runoff from adjacent agricultural lands may contribute to this elevated concentration at the shore.. Ammonium-nitrogen (NH_3-N) concentrations in Lake Arekit ranged from 73 to 83.95 µg L^{-1}, with a mean of 78.40 µg L^{-1}, also exhibiting significant spatial variation (p < 0.05). The highest ammonium-nitrogen concentration (83.95 µg L^{-1}) was measured at the macrophyte site, potentially linked to the release of feces from wetland birds, as Lake Arekit supports diverse avifauna (Tilahun et al., 2022).

Total phosphorus (TP) concentrations in Lake Arekit ranged from 194.47 to 196.13 µg L^{-1}, with a mean of 196.58 µg L^{-1}, and did not differ significantly among the studied sites (p > 0.05). The mean TP concentration in Lake Arekit was lower than that reported for Lake Ziway (262.2 µg L^{-1}; Woldesenbet & Mengistou, 2018), but higher than those reported for highland lakes such as Lake Hayq (67.14 µg L^{-1}; Fetahi et al., 2014) and Lake Ardibo (69.15 µg L^{-1}; Mohammed et al., 2024). In contrast to TP, soluble reactive phosphorus (SRP) concentrations varied significantly among sites ($p < 0.05$). The mean SRP concentration in Lake Arekit (7.73 µg L^{-1}) was lower than that reported for Lake Ziway (190 µg L^{-1}; Woldesenbet & Mengistou, 2018) and Lake Ardibo (23.84 µg L^{-1}; Mohammed et al., 2024). However, it was higher than the SRP concentrations reported for Lake Wonchi and Dendi (3.4µg L^{-1}, 2.9µg L^{-}, respectively; Degefu & Schagerl, 2015) and Lake Hayq (1.3 µg L^{-1}; Tessema et al., 2024). These variations likely reflect differences in diffuse sources, allochthonous input via surface runoff, and anthropogenic activity within the respective lake catchments.

Silica (SiO_2) concentrations exhibited significant spatial variation ($p < 0.05$, Table 2). The mean SiO_2 concentration measured in this study (6.7 mg L^{-1}) was comparable to the overall mean reported for Lake Ardibo (7.57 mg L^{-1}; Mohammed et al., 2024), but considerably lower than that of Lake Hayq (201.87 mg L^{-1}; Tessema et al., 2020). The present study's SiO^2 concentration was, however, higher than values reported for Lake Hayq (3.7 mg L^{-1}; Fetahi et al., 2014), Lake Wonchi (3.56 mg L^{-1}; Degefu & Schagerl, 2015), and Lake Ziqualla (2.28 mg L−1; Degefu & Schagerl, 2015). These variations likely reflect differences in the geological structure of the lake catchments (Ayenew & Legesse, 2007), weathering processes, sediment formation, accumulated organic matter, and diatom abundance (Wagaw et al., 2021).

4.3. Composition and Abundance of Benthic Macroinvertebrates

Macroinvertebrates collected from all study sites in this investigation represented five orders and six taxa. This observed macroinvertebrate community composition exhibited considerably lower diversity compared to previous findings in similar Ethiopian lakes. Specifically, Woldesenbet & Mengistou (2018) reported 34 families in Lake Ziway, Wondmagegn & Mengistou (2020) documented 43 families in Lake Hawassa, and Mohammed et al. (2022) identified 37 families within the Lake Tana wetlands. These discrepancies in benthic macroinvertebrate community structure likely arise from a combination of factors, including variations in water quality, urbanization, and pollution, which can lead to reduced biodiversity (Wondmagegn & Mengistou, 2020). Other potential contributing factors include seasonal fluctuations in water levels (Woldesenbet & Mengistou, 2018), differences in food availability and quantity, sediment type, substrate across study locations and variations in the duration of sampling periods (Mao et al., 2023).

This study demonstrated that human-induced disturbances influence macroinvertebrate community structure in Lake Arekit. Odonata exhibited the highest relative abundance (31.5%), followed by Hemiptera (29.6%) and Diptera (22.4%) (Table 3). The dominance of Odonata likely stems from their preference for good water quality and their voracious predatory habits. Furthermore, the abundant aquatic vegetation in Lake Arekit (Enawgaw & Wagaw, 2023), provides ideal hunting grounds for Odonata nymphs and suitable perching and oviposition sites for adults. Hemiptera represented the second most abundant group, potentially due to their diverse families and cosmopolitan distribution. This aligns with findings by Barman & Gupta (2016) and Woldesenbet & Mengistou (2018), who noted the broad habitat range occupied by Hemiptera within water bodies. Chironomidae also dominated the macroinvertebrate community, likely due to the lakebed habitat, their rapid life cycle, and tolerance of environmental extremes and disturbances. As Bouchard (2004) suggests, chironomids frequently thrive in disturbed lakes due to their physiological adaptations, life cycle strategies, and the altered conditions typical of these ecosystems. The present study's observation of these pollution-tolerant macroinvertebrate families (ranging from moderately to highly tolerant), consistent with Woldesenbet & Mengistou (2018) and Wondmagegn & Mengistou (2020), indicates a direct relationship between macroinvertebrate abundance and environmental factors such as food availability and quality, sediment type, substrate, and water quality.

4.4. Benthic macroinvertebrate Diversity

The Shannon-Wiener diversity index (H) values (Fig.3) ranged from 1.3 to 1.5 across the sampling stations and did not differ significantly among the study sites ($p > 0.05$). The highest value (1.5) was recorded at the shore site, followed by 1.4 at the macrophyte site and 1.3 at the open water site. This value is less than what was reported by Wondmagegn & Mengistou (2020), and Woldesenbet & Mengistou (2018) Lake Hawassa and Lake Ziway, respectively. The variation likely resulted from differences in food source availability (both quality and quantity), trophic structure, and environmental stress levels at each site. These results are consistent with the findings of Kuma et al. (2022) and Hamdi et al. (2024), who reported a correlation between environmental stability and biodiversity, with stable environments exhibiting higher Shannon-Wiener diversity indices (H) and unstable environments lower ones.

Lake Arekit exhibited relatively moderate diversity, with Shannon-Wiener index (H') values above 1. According to Wilhm & Dorris (1968), water quality can be classified based on species diversity: H' > 3 indicates clean water, H' = 1-3 moderately polluted water, and H' < 1 heavily polluted water. Similarly, Staub et al. (1970) categorized H' < 1 as heavily polluted, H' = 1-2 as moderately polluted, H' = 2-3 as lightly polluted, and H' > 3 as slightly polluted. Based on the species diversity scales proposed by Wilhm & Dorris (1968) and Staub et al. (1970), Lake Arekit is classified as moderately polluted (H' = 1.3 - 1.5). This moderate pollution, and consequently the macroinvertebrate diversity within Lake Arekit, may be negatively impacted by environmental stressors in the littoral zone. These stressors could include shoreline modification, municipal waste discharge, and construction activities within the littoral area. Reduced diversity in the presence of stressors has also been reported in other Ethiopian water bodies, such as the Kebena and Akaki Rivers (Beyene et al., 2009), the Blue Nile River (Wosnie & Wondie, 2014), Lake Tana (Gezie et al., 2017), Lake Hawassa (Wondmagegn & Mengistou, 2020), and Lake Ziway (Woldesenbet & Mengistou, 2018).

Macroinvertebrate community diversity was also assessed using Pielou's Evenness (J) and Equitability, similar to the Shannon-Wiener index. Following Mandeville (2002), evenness and equitability values range from 0 to 1. A value of 0 indicates dominance by a few species with most others rare or absent, reflecting an uneven species distribution. Conversely, a value of 1 signifies equal abundance across all species. In this study, evenness ranged from 0.61 to 0.89, and equitability from 0.73 to 0.93. The highest values for both metrics were observed at the lake shore site (Fig. 2), demonstrating significant spatial variation among sites ($p < 0.05$). This variation likely reflects differences in water quality. This finding aligns with Wosnie & Wondie (2014) and Gezie et al. (2017), who also reported spatial variation in Pielou's evenness (J) index along the Blue Nile River and Lake Tana, respectively, attributing it to variations in habitat physicochemical characteristics. Benthic macroinvertebrate equitability also showed significant spatial variation ($p < 0.05$), with the highest value (0.93) at the shore site and the lowest (0.73) at the open water site. This trend mirrored that of Pielou's evenness (J) index at each site. The high evenness value at the shore site (0.89, Fig. 3) likely results from a more homogenous distribution of individuals among the collected taxa.

4.5. Factors Affecting Macro-invertebrate Community in Lake Arekit

The community structure of macroinvertebrates is regulated by a variety of environmental factors, including food availability and quantity, sediment type, substrate, and water quality, all of which are critical for their distribution and abundance in lakes (Wondmagegn & Mengistou, 2020; Mohammed et al., 2022; Mao et al., 2023). In this study, the RDA plot effectively visualizes how environmental factors, particularly in the present study SRP, TDS, NH_3-N, and habitat characteristics, structure the observed macroinvertebrate community composition in

Lake Arekit. The RDA triplot shows that the first two axes explain 93.2% of the cumulative variance in the species-environment relationship. The remaining 6.8% of the variance may be attributable to other biotic and abiotic factors not included in this analysis, such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), water level fluctuations, sediment structure, food availability, organic matter in silt, and pesticides.

In this study, the Chironomidae, Gerridae, Coenagrionidae and Hirudinidae families showed a positive association with nutrient levels. This aligns with previous research (Gerber & Gabriel, 2002; Bouchard, 2004) indicating that these families exhibit moderate to high pollution tolerance. The observed increase in diversity of these families with increasing nutrient levels supports this finding. Hirudinidae are known to inhabit various trophic levels in lakes (Khan et al., 2024). Chironomidae, Gerridae, and Coenagrionidae can tolerate suboptimal water quality conditions associated with eutrophication and elevated nitrate concentrations, likely due to their inherent tolerance (Vilenica et al., 2024).

Baetidae exhibited a strong negative association with most nutrients and, conversely, a strong positive association with turbidity and total dissolved solids. This result is consistent with the findings of Woldesenbet & Mengistou (2018), suggesting that Baetidae can tolerate high turbidity and total dissolved solids. In this study, Notonectidae showed a strong positive correlation with Total Phosphorus (TP), pH, and temperature, but a strong negative association with turbidity and Total Dissolved Solids (TDS) (Figure). This contrasts with the findings of Wondmagegn & Mengistou (2020), who noted that Notonectidae typically inhabit relatively undisturbed and less polluted areas with minimal disturbance and low nutrient and ion concentrations. Fentaw et al. (2024) also reported that these taxa generally prefer less polluted and disturbed habitats.

5. Conclusion

This study demonstrates that Lake Arekit's benthic macroinvertebrate communities are significantly shaped by physicochemical gradients and anthropogenic pressures, with pollution-tolerant taxa (e.g., Chironomidae, Hemiptera) dominating nutrient-enriched, disturbed habitats, while sensitive taxa decline under turbid conditions. Spatial analysis revealed elevated nutrient concentrations at anthropogenically impacted shoreline sites, correlating with reduced macroinvertebrate diversity and homogenized community structure. Redundancy Analysis (RDA) identified ammonium, turbidity, and total dissolved solids as key drivers explaining macroinvertebrate species-environment interactions. These findings underscore Lake Arekit's ecological degradation and position macroinvertebrates as effective bioindicators of freshwater health in tropical highland lakes. To mitigate eutrophication and habitat loss, integrated watershed management including reduced fertilizer runoff, wastewater treatment, and littoral zone protection is urgently needed. This work provides a model for assessing anthropogenic impacts on freshwater ecosystems in rapidly developing regions, bridging ecological research with actionable conservation strategies.

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Conflicts of Interest

The authors report no conflicts of interest.

Data Availability Statement

The data supporting the study's conclusions are available from the corresponding author upon request.

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