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Water and Sediment Chemistry as Drivers of Macroinvertebrates and Fish Assemblages in Littoral Zones of Subtropical Reservoirs

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Abstract: Reservoirs are human-made ecosystems with diverse purposes that benefit humans both directly and indirectly. They however cause changes in geomorphological processes such as sediment cycling and influence the composition and structure of aquatic biota. This study aimed to identify water and sediment quality parameters as drivers of macroinvertebrates and fish communities during the cool-dry and hot-wet seasons in the littoral zones of three subtropical reservoirs (Albasini, Thathe and Nandoni). Macroinvertebrates and fish were collected from three sites (n = 3 from each site) in each reservoir. A total of 501 and 359 macroinvertebrates and fish individuals were collected throughout the sampling period, respectively. The present study employed a two-way ANOVA in conjunction with redundancy analysis (RDA) to assess the relationships that exist between water and sediment variables, macroinvertebrates diversity and species abundances across seasons. Based on the two-way ANOVA model, significant differences were observed across reservoirs for evenness, Simpson's diversity, and total abundance, while seasonal differences were observed for most metrics, with exception for evenness. The RDA results identified four water variables (i.e., water temperature, oxidation–reduction potential, pH and conductivity) and one sediment metal (Mg) as the most important parameters in driving the fish community structure. Field observations and metal results attest that the Nandoni reservoir shows high concentrations of metals in sediments as compared to other reservoirs, suggesting that anthropogenic activities such as car washing, brick making, recreation, fishing, wastewater treatment work and landfill site may be the major contributor of metals to the Nandoni reservoir, which accumulate in the littoral zones. Findings of this study highlight the need to analyze reservoir ecological conditions at several scales. The study of macroinvertebrates and fish, water, and sediment chemistry in the littoral zone laid the groundwork for proposing measures for conserving aquatic ecosystems.

Keywords: aquatic ecosystems; biomonitoring; community structure; littoral macroinvertebrates; macrozoobenthos; reservoir ecology

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1. Introduction

Freshwater is among vital natural resources that play an essential role in supporting and maintaining life on Earth [1]. Freshwater constitutes approximately 2.5 percent of the overall water volume on planet Earth, but in turn, it serves as habitat and the foundation of aquatic biodiversity [2]. Aquatic ecosystems such as lakes, ponds, streams, rivers, and wetlands provide important services for human life such as water security, food security, and economic productivity [3–5]. Water is not only a life-sustaining resource for all biotic components, but also a major factor contributing to all developmental activities associated with environmental and cultural processes [6]. However, as tolerating as freshwater ecosystems are, they are vulnerable to the increasing pressure and threats posed by global anthropogenic pollution from activities such as agriculture, development of urban areas, and mining [7–9].

According to Dalu et al. [10], water pollution is a major management concern in developing countries, with many rivers and streams classified as endangered, as they are subjected to untreated solid waste, wastewater discharge, higher population, stormwater, and agricultural runoff. A study by Dalu and Chauke [11] indicated that anthropogenic activities (for example, cattle grazing and cultivation) contribute to increased nutrient concentration in freshwater ecosystems such as wetlands, which have a significant negative effect on macroinvertebrate communities. Enough evidence from various studies shows that activities within agricultural sectors tend to have a noticeable effect on water systems in comparison to activities such as forestry and urban areas [12–14].

Among the aquatic biota, macroinvertebrates and fish are generally highly sensitive organisms and their dynamics can seriously be affected by changes in water quality [15,16]. Due to anthropogenic activities, fish and macroinvertebrate communities are threatened, leading to an unbalanced food-web structure in freshwater ecosystems [17,18]. These organisms possess various attributes such as a high production rate, a faster growth rate, and the ability to provide a meaningful ecological state over time in a particular water body [19,20]; thus, they can be used for bioassessment of the ecological integrity of freshwater ecosystems. Although these organisms usually respond to changes in the quality of the water, their sensitivity may differ significantly [21].

Macroinvertebrates and fish communities are comprised of a variety of taxa with varying degrees of pollution tolerance [22,23]. While this has been well studied in different aquatic ecosystems, changes in community structure of macroinvertebrates and fish have been less explored in subtropical standing water bodies [11,17]. The physicochemical conditions of reservoirs water and sediments are intrinsically intertwined; it is therefore difficult to disregard the dynamics of sediment flora and fauna if one wants to completely comprehend these aquatic ecosystems [24,25]. For instance, physical and chemical variable concentrations are important in structuring the diversity of macroinvertebrates and fish, with implications for biodiversity conservation in these water bodies [26,27]. These dynamics are important to understand because catchment activities can be sources of various metals and nutrients that are washed to the reservoirs through runoff and can enter the reservoirs, thus altering water quality and aquatic food-web functioning [28,29]. Sediment may also contain nutrients, heavy metals, and organochlorine pesticides that are released into the water column and then into the food chain [30]. As a result, they contribute significantly to a variety of biotic and abiotic processes in reservoirs [31].

Given the importance of freshwater in promoting healthy aquatic biodiversity, rapid assessments are required to detect management and monitoring strategies to ensure the safety of aquatic ecosystems and to aid in the documentation of policies to support these measures. This study assessed the seasonal patterns in macroinvertebrates and fish communities, and their diversity matrices in response to seasonal variations in the littoral zones of subtropical reservoirs. These reservoirs are important ecological features because they are habitats for many fauna and flora, foraging ground for crocodiles and a source of water supply for many local communities around the Vhembe district. This study hypothesized that (i) water and sediment chemistry would cause changes in macroinvertebrates and fish communities due to various anthropogenic activities practiced in the catchment as communities respond differently to changes in anthropogenic pressures and (ii) the hot-wet season will have more abundant and diverse macroinvertebrates and fish than the cool-dry season because different seasons changes aquatic dynamics.

2. Methods and Materials

2.1. Ethical Clearance

Macroinvertebrates and fish samples were collected following ethical clearance approved by the research committee of the University of Venda (Ethical clearance No. SES/20/ERM/14/1611).

2.2. Study Area

This research was conducted during the cool-dry and hot-wet seasons of the year 2022 in three selected water supply reservoirs, namely Nandoni (22°59′20″ S, 30°36′27″ E), Thathe (22°56′45″ S 30°20′7″ E) and Albasini (23°6′30″ S 30°7′48.2″ E), within the Vhembe district, Limpopo Province, South Africa (Figure 1). These reservoirs are located within the Luvuvhu River Catchment (LRC), which connects the three reservoirs and many tributaries [32], and forms part of the larger Limpopo River system. The selection of these reservoirs for sampling is based on: (1) the river connection that exists within the catchment with the reservoirs, (2) the biodiversity they inhabit, (3) the activities that are being practiced adjacent to these dams which are associated with land degradation, and (4) the role that they play in local communities (water provision). The Luvuvhu River rises as a steep mountain stream in the south-easterly slopes of the Soutpansburg mountains and runs through a variety of landscapes for approximately 200 km before joining the Limpopo River near to Pafuri in the Kruger National Park [33,34]. The Nandoni reservoir is located in the middle section of the LRC, whereas the Albasin and Thathe reservoirs are located in the upper LRC, with Thathe captured along the tributary of Mutshundudi River, which is steep, narrow, and dominated by cobble riffles [33]. The mean annual rainfall in the LRC is 608 mm and the mean annual runoff is 520 × 10^6 m^3. The topography varies from 200 m to 1500 m, which influences rainfall and runoff distribution in the catchment [35].

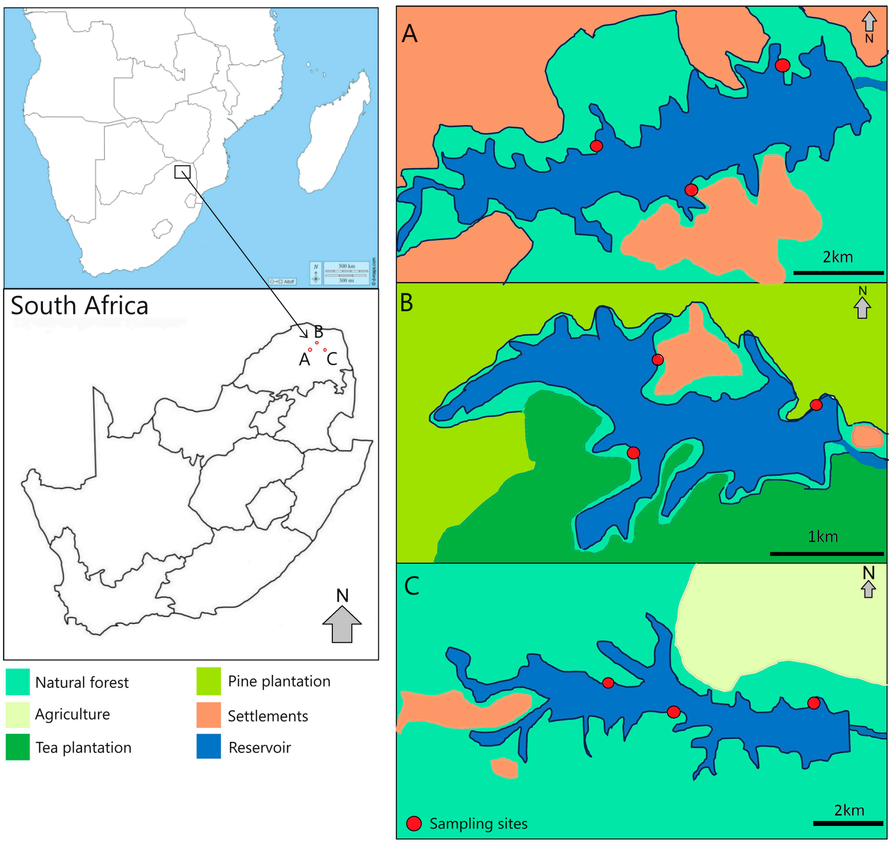

Figure 1. Map showing the location of the sample collection sites and land use activities across three reservoirs, (**A**) the Nandoni reservoir, (**B**) the Thathe reservoir, and (**C**) the Albasini reservoir, within the Luvuvhu River Catchment, Limpopo prince, South Africa.

2.3. Determining Environmental Variables

2.3.1. Physicochemical Parameters of Water

During sampling, pH, conductivity (µS cm^{-1}), total dissolved solids (mg L^{-1}), resistivity (ohm), salinity (ppm), oxygen redox potential (mV), and water temperature (°C) were measured in situ at each site (*n* = 3; ~3 m apart) per season using a portable multiparameter probe PCTestr 35 (Eutech/Oakton Instruments, Singapore). All physicochemical parameters measurements were performed before macroinvertebrates and fish sampling. These measurements were performed 3 m away from where macroinvertebrates and fish were collected to avoid habitat disturbance [8].

2.3.2. Sediment Chemistry Variables

Sediment samples (*n* = 2) were collected from each site per season (2 m away from where macroinvertebrates and fish were sampled) using acid-washed wooden splints, and in order to prevent cross-contamination, each integrated sample was placed in a fresh plastic Ziplock bag. The composite sediment samples were promptly sealed and packaged in an ice-filled cooler box before being transported to the University of Venda Pollution Laboratory for analysis within 24 h. Upon arrival to the laboratory, the samples were placed in an oven and dried at 60 °C for 72 h. Samples were then taken out and disaggregated in a porcelain mortar. After using a riffle splitter to homogenize the dried sediment samples, a sediment subsample weighing 0.5 kg was separated and transported to BEMLAB in Cape Town for further analysis. The concentrations of the following elements were analyzed for each site and season: pH, phosphorus (P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), copper (Cu), zinc (Zn^{2+}), manganese (Mn), boron (B), iron (Fe), carbon (C), sulfur (S), ammonium (NH_4^+), and soil organic matter (SOM). Briefly, for each sediment sample, ammonia and phosphorus were analyzed using a SEAL Auto-Analyzer 3 coupled with high resolution and Bray-2 extract as described by Bray and Kurtz [36] and following Allen et al. [37], an inductively coupled plasma atomic emission spectroscopy (ICPMS) instrument was used to measure elements such as K, Zn, Na Ca, Cu, Mg, Mn, B, Fe, and S (see Dalu et al. [38,39] for detailed methods).

2.4. Littoral Macroinvertebrates Sampling

Macroinvertebrates were collected at each site (water depth 0.1–0.6 m) and season using a handheld kick net (frame 30 cm × 30 cm, mesh size 500 µm) by submerging the sample kick net for five minutes while kicking the benthic substrate to loosen any attached taxa on sand and rocks, then sweeping and pulling the net through macrophytes along the 10 m transect in the littoral zones. This sampling procedure allowed a good and enough representation of macroinvertebrates individual per unit time (see Dalu et al. [23] for methodology). The net was then taken out of the water column and macroinvertebrates were carefully separated from the net, and then preserved in 70% ethanol in labelled 500 mL polyethylene containers for further processing in the laboratory. In the laboratory, macroinvertebrates were sorted under a dissecting Olympus microscope using forceps and identified to the family level following the guide by Fry [40]. The results of macroinvertebrates were presented as relative abundances.

2.5. Littoral Fish Sampling

A seine net was used to collect fish taxa in the littoral zones of the reservoirs (<1.5 m deep). A seine net (5 m long) was pulled into the reservoir in a straight-line motion and dragged across a 20 × 20 m transect within the reservoir by swiping all fish species found in the covered section (*n* = 2). All captured fish were removed from the seine net and put into different 20 L buckets containing water. Fish were identified to the species level on site, and the data were recorded; then fish were released back to the reservoir immediately after identifying each of them. The results of fish were presented as relative abundances.

2.6. Data Analyses

Macroinvertebrate diversity metrices (evenness, Margalef's diversity taxa richness, Shannon–Wiener diversity, and Simpson's diversity) were calculated using a macroinvertebrate community dataset in PAST version 4.03. The effects of different reservoirs (three levels: Albasini, Nandoni, and Thathe), and seasons (two seasons; hot-wet, cool dry), and their interaction, on environmental variables (i.e., water and sediments) and macroinvertebrates diversity metrics, i.e., evenness, Margalef's diversity index, taxa richness, Shannon–Wiener diversity, Simpson's diversity index and total abundance were examined using a factorial two-way ANOVA with Tukey's post hoc after testing for homogeneity of variances (Levene's test, $p > 0.05$) and normality of distribution (Shapiro–Wilk test, $p > 0.05$) SPSS v16.0 (SPSS Inc., Chicago, IL, USA, 2007) were determined. In all analyses, significance was inferred at $p < 0.05$.

Furthermore, distance-based Permutational Analysis of Variance (PERMANOVA) based on Bray–Curtis dissimilarities were employed for biological data and 9999 permutations along with Monte Carlo tests were utilized to analyze differences in fish and macroinvertebrate communities using PERMANOVA + PRIMER version 6 [41].

For all community analyses, all macroinvertebrate and fish abundance data were square-root transformed in order to reduce skewness, while all environmental variable data except for pH were log $(x + 1)$ transformed. We used detrended canonical correspondence analysis (DCCA) to determine whether unimodal or linear methods would be appropriate for the ordination analysis. The length of the gradient was examined and since the longest gradient was <3.0, a linear constrained method, i.e., redundancy analysis (RDA), was employed. An RDA was then performed on the transformed macroinvertebrate and fish abundance data to mainly examine the links between species composition and the selected environmental variables. All variables that were significant ($p < 0.05$) were subjected to RDA forward selection based on environmental variables and sediment chemistry variables to identify a minimal subset of environmental variables that were important to drive the macroinvertebrate and fish community structure (Monte Carlo test with 9999 permutations). The software Canoco version 5.1 was used for the analysis [42].

3. Results

3.1. Environmental Variables (Water and Sediment Chemisty)

Differences in water chemistry variables over the sampling reservoirs and different seasons are highlighted in Table 1. Across reservoirs and seasons, temperature (mean range, 18.7–28.4 °C), pH (mean range, 7.5–8.4), conductivity (mean range, 78.3–421.2 µS cm^{-1}), TDS (mean range, 58.1–142.0), salinity (mean range, 462.6–2246.1 ppm), resistivity (mean range, 720.3–1665.0 °C ohm) and ORP (mean range, 41.8–54.6 mV) differed substantially (Table 1). Significant differences were observed for temperature (ANOVA: F = 145.270; $p < 0.001$), pH (ANOVA: F= 9.631; $p = 0.003$), conductivity (ANOVA: F = 148.528; $p < 0.001$), TDS (ANOVA: F = 127.415; $p < 0.001$), and ORP (ANOVA: F = 48.958; $p < 0.001$), while seasonal differences were observed for temperature (ANOVA: F = 1862.535; $p < 0.001$), pH (ANOVA: F = 21.715; $p = 0.001$), conductivity (ANOVA: F = 1732.485; $p < 0.001$), TDS (ANOVA: F = 16.652; $p = 0.002$), and salinity (ANOVA: F = 4.825; $p = 0.048$) and reservoirs × seasons interactions were observed for temperature (ANOVA: F = 22.449; $p < 0.001$), pH (ANOVA: F = 3.915; $p = 0.049$), conductivity (ANOVA: F = 119.397; $p < 0.001$), TDS (ANOVA: F = 199.144; $p < 0.001$), and ORP (ANOVA: F = 4.543; $p = 0.034$) (Table 2). In general, significant differences were detected when comparing reservoirs.

According to post hoc comparison, across reservoirs, significant differences were observed for temperature, i.e., Albasini vs. Thathe ($p < 0.001$) and Nandoni vs. Thathe ($p < 0.001$), pH, i.e., Albasini vs. Thathe ($p = 0.018$), Nandoni vs. Thathe ($p = 0.003$), conductivity, i.e., Albasini vs. Nandoni ($p < 0.001$), Albasini vs. Thathe ($p < 0.001$), Nandoni vs. Thathe ($p < 0.001$), TDS, i.e., Albasini vs. Thathe ($p < 0.001$), Nandoni vs. Thathe ($p < 0.001$) and ORP, i.e., Albasini vs. Nandoni ($p < 0.001$), Nandoni vs. Thathe ($p < 0.001$).

Table 1. Mean (±standard deviation) water chemistry variables measured across sampling reservoirs (i.e., Albasini, Nandoni and Thathe) and different seasons (hot-wet and cool-dry). Abbreviations: TDS—total dissolved solids; ORP—oxidation–reduction potential.

Variables	**Unit**	**Seasons**	**Reservoirs**		
			Albasini	**Nandoni**	**Thathe**
Temperature	°C	Cool-dry	22.4 ± 10.3	20.8 ± 9.5	18.7 ± 8.5
		Hot-wet	27.6 ± 12.9	28.4 ± 13.3	25.5 ± 11.9
pH		Cool-dry	7.5 ± 2.9	8.3 ± 3.3	7.5 ± 2.9
		Hot-wet	8.3 ± 3.3	8.4 ± 3.3	8.1 ± 3.2
Conductivity	$\mu S\ cm^{-1}$	Cool-dry	128.1 ± 148.2	421.2 ± 209.8	316.0 ± 157.1
		Hot-wet	205.7 ± 102.3	169.4 ± 85.0	78.3 ± 39.6
TDS	$mg\ L^{-1}$	Cool-dry	106.8 ± 52.5	132.5 ± 65.4	113.3 ± 55.8
		Hot-wet	142.0 ± 70.2	123.2 ± 60.8	58.1 ± 29.7
Salinity	ppm	Cool-dry	481.5 ± 331.0	1902.4 ± 1417.6	2246.1 ± 1749.6
		Hot-wet	462.6 ± 232.6	686.7 ± 501.6	688.3 ± 504.9
Resistivity	ohm	Cool-dry	1541.5 ± 950.2	778.0 ± 743.4	720.3 ± 787.9
		Hot-wet	1665.0 ± 842.3	1397.0 ± 835.5	1304.6 ± 810.1
ORP	mV	Cool-dry	43.3 ± 20.8	50.1 ± 24.3	43.5 ± 20.9
		Hot-wet	41.8 ± 20.1	54.6 ± 26.5	46.5 ± 22.4

Table 2. Two-way analysis of variance (ANOVA) based on water and sediment variables and macroinvertebrate and fish diversity metrics for sampled reservoirs (i.e., Albasini, Nandoni and Thathe: *df* = 2) and seasons (hot-wet and cool-dry: *df* = 1). F-values are discerned with type III sums of squares via. Satterthwaite's method. Significant *p*-values are in bold.

Variables	**Reservoirs**		**Seasons**		**Reservoirs × Seasons**	
	F	***p***	**F**	***p***	**F**	***p***
Water chemistry variables						
Temperature	**145.270**	**<0.001**	**1862.535**	**<0.001**	22.449	**<0.001**
pH	**9.631**	**0.003**	**21.715**	**0.001**	**3.915**	**0.049**
Conductivity	**148.528**	**<0.001**	**1732.485**	**<0.001**	**119.397**	**<0.001**
TDS	**127.415**	**<0.001**	**16.652**	**0.002**	**199.144**	**<0.001**
Salinity	2.100	0.165	**4.825**	**0.048**	1.212	0.332
Resistivity	1.491	0.264	2.115	0.172	0.276	0.764
ORP	**48.958**	**<0.001**	5.620	0.035	**4.543**	**0.034**
Sediment chemistry variables						
pH	0.76	0.927	0.757	0.401	**4.882**	**0.028**
P	2.655	0.111	0.207	0.657	2.038	0.176
NH_4^+	0.681	0.525	0.531	0.480	0.567	0.582
K	1.690	0.226	1.625	0.227	0.482	0.629
Ca	0.312	0.738	0.285	0.603	0.303	0.744
Mg	1.242	0.323	0.571	0.465	1.841	0.201
Cu	0.403	0.677	0.001	1.000	0.244	0.787
Zn	0.131	0.878	0.001	0.971	3.154	0.079
Mn	0.582	0.574	0.096	0.763	2.639	0.112
B	1.165	0.317	1.559	0.236	0.324	0.730
Fe	0.087	0.917	0.048	0.830	1.024	0.388
C	0.956	0.412	3.119	0.103	0.719	0.507
S	1.165	0.345	0.235	0.637	**5.459**	**0.021**
Macroinvertebrate diversity metrics						
Evenness	**49.408**	**<0.001**	1.353	0.267	**4.228**	**0.041**
Margalef's diversity	**40.745**	**<0.001**	0.267	0.615	**18.737**	**<0.001**
Taxa richness	**52.125**	**<0.001**	0.042	0.842	**7.292**	**0.008**
Shannon–Wiener diversity	**15.887**	**<0.001**	3.650	0.080	3.399	0.068
Simpson's diversity	**7.549**	**0.008**	**5.985**	**0.031**	2.046	0.172
Total abundance	**51.128**	**<0.001**	0.139	0.716	**4.794**	**0.029**

Table 2. *Cont.*

Variables	Reservoirs		Seasons		Reservoirs × Seasons	
	F	*p*	F	*p*	F	*p*
Fish diversity metrics						
Evenness	29.031	**<0.001**	0.008	0.928	**10.045**	**0.003**
Margalef's diversity	0.309	0.740	**8.112**	**0.015**	**4.409**	**0.037**
Taxa richness	3.040	0.085	**16.000**	**0.002**	2.560	0.119
Shannon–Wiener diversity	1.487	0.265	**20.071**	**0.001**	**9.163**	**0.004**
Simpson's diversity	**9.824**	**0.003**	**17.173**	**0.001**	**15.023**	**0.001**
Total abundance	**15.031**	**0.001**	**6.870**	**0.022**	0.046	0.956

Generally, in the Albasini reservoir, high mean sediment chemistry variable concentrations were observed for pH (mean, 7.2) and Fe (565.3 mg kg^{-1}). In the Nandoni reservoir, high mean sediment chemistry variable concentrations were observed for P (mean, 249 mg kg^{-1}) and Ca (mean, 21.3 mg kg^{-1}). Lastly, in the Thathe reservoir, high mean sediment chemistry variable concentrations were observed for pH (mean, 7.2), NH_4^+ (mean, 123.5), K (mean, 666.7 mg kg^{-1}), Mg (mean, 20.2 mg kg^{-1}), Cu (mean, 16.7 mg kg^{-1}), Zn (mean, 2.2 mg kg^{-1}), Mn (mean, 398.1 mg kg^{-1}), B (mean, 1.2 mg kg^{-1}), C (mean, 2.9%) and S (mean, 155.9 mg kg^{-1}). With regard to seasons across reservoirs, high mean sediments chemistry was observed for pH, P, Ca, Cu, Zn, Mn, C during the hot-wet seasons and pH, NH_4^+, K, Mg, B, Fe and S during the cool-dry season. According to two-way ANOVA, all the sediment variables were found to be similar between the study reservoirs and seasons ($p > 0.05$; Table 2).

3.2. Macroinvertebrate Communities

A total of 501 macroinvertebrate individuals belonging to 21 families and 7 orders were identified within three selected water bodies (Table 3). In terms of orders, Hemiptera (28.6%) was the dominating order followed by Odonata (23.8%) and Coleoptera (14.3%). Overall, bladder snails Physidae were the most dominant family group, accounting for 31.7% of the total individuals across sampling reservoirs and seasons, with freshwater shrimp Atyidae being the second most abundant family group (12.0%). Non-biting midges Chironomidae were the third most abundant accounting for 8.0%. Based on the two-way ANOVA model, significant differences were observed across sampling reservoirs for all five metrics ($p < 0.05$; Table 2), while seasonal differences were observed for Simpson's diversity (ANOVA: F = 5.989; $p = 0.031$). Reservoirs and season interaction indicated significant differences for most of the metrics ($p < 0.05$) (Table 2), with the exception for Shannon–Wiener diversity and Simpson's diversity ($p > 0.005$).

Table 3. Mean relative abundances (%) of the dominant macroinvertebrate species and diversity metrics observed across two seasons for the study site categories: Albasini, Nandoni and Thathe reservoirs.

Order	Taxa	Cool-Dry			Hot-Wet		
		Albasini	Nandoni	Thathe	Albasini	Nandoni	Thathe
Mollusca	Thiaridae		26.9	15.7			5.7
Mollusca	Lymnaeidae	3.6			2.3		
Mollusca	Physidae	57.1		15.7	37.9	5.6	
Crustacea	Atyidae	3.6		5.9	23.5	21.3	2.9
Crustacea	Potamonautidae	3.6	19.2	5.9			8.6
Odonata	Aeshnidae	2.4		5.9	3.0	6.7	
Odonata	Lestidae			3.9		4.5	
Odonata	Libellulidae	3.0		7.8	0.8	10.1	14.3
Odonata	Coenagrionidae	1.8	15.4	3.9	3.8		8.6
Odonata	Gomphidae	2.4	15.4	2.0	7.6	1.1	

Table 3. *Cont.*

Order	Taxa	Cool-Dry			Hot-Wet		
		Albasini	Nandoni	Thathe	Albasini	Nandoni	Thathe
Coleoptera	Dytiscidae	4.8	19.2	7.8		5.6	
Coleoptera	Gyrinidae	6.0			0.8		
Coleoptera	Hydroptilidae	3.0					
Hemiptera	Nepidae	3.6		5.9	6.1	10.1	
Hemiptera	Notonectidae			9.8		9.0	
Hemiptera	Gerridae				3.0	7.9	
Hemiptera	Belostomatidae	4.2		2.0			8.6
Hemiptera	Aphelocheiridae			3.9	2.3		
Hemiptera	Corixidae		3.9	3.9			
Ephemeroptera	Baetidae	1.2					17.1
Diptera	Chironomidae				9.1	18.0	34.3
Diversity metrics							
Evenness		0.4	0.9	0.9	0.6	0.9	0.9
Margalef's diversity		2.8	3.2	1.1	2.4	2.5	2.1
Taxa richness		14	6	15	12	11	8
Shannon–Wiener diversity		1.7	2.2	1.0	1.8	2.1	1.6
Simpson's diversity		0.7	0.9	0.6	0.8	0.9	0.8

Using PERMANOVA, macroinvertebrate community structure was found to differ significantly among reservoirs (PERMANOVA: Pseudo-F = 9.8429, $p(MC) < 0.001$) and seasons (PERMANOVA: Pseudo-F = 7.07, $p(MC) < 0.001$). The interaction between reservoirs and seasons was also found to be different (PERMANOVA: Pseudo-F = 2.7995, $p(MC) < 0.001$). Pairwise comparisons highlighted significant differences in macroinvertebrate community structure between reservoirs, i.e., Albasini vs. Nandoni ($p(MC) = 0.0018$), Albasini vs. Thathe $p(MC) = 0.0023$) and Nandoni vs. Thathe ($p(MC) = 0.0015$).

3.3. Fish Communities

In total, 359 fish individuals were identified within the three reservoirs over the study period, with 111, 176, and 69 individuals being identified in Albasini, Nandoni, and Thathe, respectively. Overall, Mozambique tilapia *Oreochromis mossambicus* (Peters, 1852) was the most dominant taxa accounting for 33.7% of the total individuals, followed by Banded tilapia *Tilapia Sparrmanii* (Smith, 1840), largemouth Bass *Micropterus salmoides* (Lacépède, 1802), Straightfin Barb *Enteromius paludinosus* (Peters, 1852) and sharptooth catfish *Clarias gariepinus* (Burchell, 1822) accounting for 9.7%, 8.9%, 8.6% and 7.5%, respectively (Table 4). During the hot-wet and cool-dry seasons across all reservoirs, *O. mossambicus* was the most dominant taxa accounting for 29.2% and 40.1%, respectively (Table 4).

Table 4. Mean relative abundances (%) of the dominant fish species and diversity metrics observed across two seasons for the study site categories: Albasini, Nandoni and Thathe reservoirs.

Species	Cool-Dry			Hot-Wet		
	Albasini	Nandoni	Thathe	Albasini	Nandoni	Thathe
Clarias gariepinus (Burchell, 1822)			13.3	12.2	11.9	16.1
Micropterus dolomieu (Lacépède, 1802)	7.9			39.0	18.6	
Micropterus salmoides (Lacépède, 1802)	23.7	5.9			6.8	16.1
Oreochromis mossambicus (Peters, 1852)	15.8	52.9	26.7	7.3	23.7	6.5
Coptodon rendalli (Boulenger, 1897)	13.2	5.9	26.7	7.3	5.1	9.7
Tilapia sparrmanii (Smith. 1840)	18.5	14.7		4.9	5.1	6.5
Enteromius afrohamiltoni (Crass, 1960)	10.5				3.4	
Gambusia affinis (Baird and Girard, 1853)			33.3			6.5
Enteromius paludinosus (Peters, 1852)		14.7		12.2	13.6	16.1
Enteromius unitaeniatus (Günther, 1866)	13.2	5.9			8.5	6.5

Table 4. *Cont.*

Species	Cool-Dry			Hot-Wet		
	Albasini	**Nandoni**	**Thathe**	**Albasini**	**Nandoni**	**Thathe**
Labeo rosae (Steindachner, 1894)					3.4	
Mesobola brevianalis (Boulenger, 1908)				7.3		16.1
Glossogobius guiris (Hamilton, 1822)				4.9		
Labeo cylindricus (Peters, 1852)				4.9		
Diversity metrics						
Evenness	0.8	0.5	0.5	0.7	0.7	0.8
Margalef's diversity	1.9	1.3	1.3	2.1	2.4	2.0
Taxa richness	7	6	3	9	10	9
Shannon–Wiener diversity	1.6	1.0	1.0	1.7	1.9	1.7
Simpson's diversity	0.8	0.5	0.5	0.8	0.8	0.8

Based on the two-way ANOVA model, significant differences were observed across sampling reservoirs for evenness, Simpson's diversity and total abundance ($p < 0.05$; Table 2), while seasonal differences were observed for most metrics, with exception for evenness ($p > 0.05$), whereas, reservoirs and season interaction indicated significant differences for most of the metrics ($p < 0.05$) (Table 2), with exception for taxa richness and total abundance ($p > 0.05$). Using PERMANOVA, no significant differences in fish community structure were observed across sites PERMANOVA: Pseudo-F = 1.168, p(MC) = 1.149), seasons (PERMANOVA: Pseudo-F = 0.616, p(MC) = 0.627) and sites and seasons interaction (PERMANOVA: Pseudo-F = 1.352, p(MC) = 0.239).

3.4. The Influence of Environmental Parameters on Macroinvertebrate Communities

The RDA first and second axes of the selected exploratory variables accounted for 37.99% of the total macroinvertebrate community data variance. Of the 19 physicochemical variables, the macroinvertebrate community structure across the three reservoirs and the two sampling seasons was found to be significantly associated with water temperatures, ORP, TDS, and conductivity (Figure 2a). Water temperature and TDS were positively associated with the first axis, while conductivity was negatively associated with the second axis (Figure 2a). The hot-wet season was clearly separated along the first axis from the cool-dry season. According to their correlation with the axes, the environmental variables determining the gradients in the RDA diagrams were temperature, conductivity, ORP and TDS (Table 5). Only A1 (Albasani reservoir) appears to be clearly associated to Aeshnidae, Nepidae and Gerridae which were positively correlated with high water temperature and high TDS (Figure 2a).

3.5. The Influence of Environmental Parameters on Fish Communities

The RDA first and second axes of the selected exploratory variables accounted for 56.38% of the total fish community data variance (Figure 2b). The RDA identified five variables (i.e., water temperature, ORP, water pH, Mg (in sediments), and conductivity (water) as the most important in structuring the fish community structures (Figure 2b). Water temperature, ORP, and pH were positively associated with the first axis while conductivity was negatively associated with the second axis (Figure 2a), while water temperature is positively associated with the first axis, and conductivity is negatively associated with the second axis (Figure 2b). The hot-wet season was separated along the second axis from the cool-dry season. According to their correlation with the axes, the environmental variables determining the gradients in the RDA diagrams were temperature, pH, ORP and conductivity (Table 5). The fish that were associated with the hot-wet seasons were *E. unitaeniatus*, *E. paludinosus*, and *L. rosae* which were associated with high water temperature and high ORP. While the fish species that were in the cool-dry season were *G. affinis*, *C. rendalli*, and *T. sparrmanii* (Figure 2b).

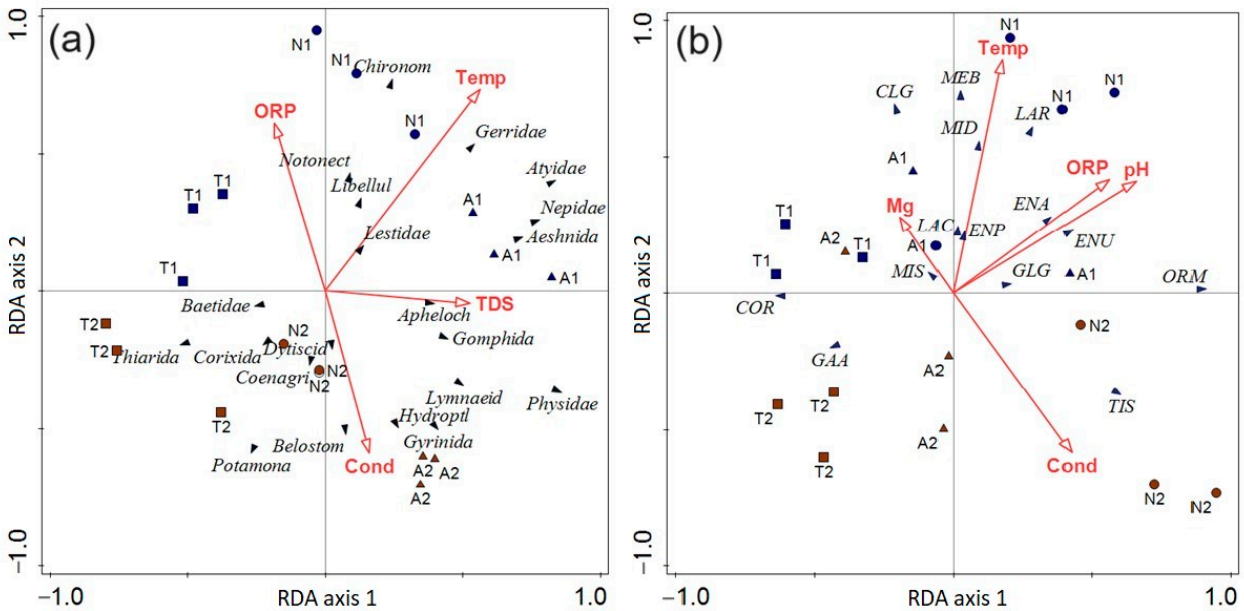

Figure 2. (**a**) Redundancy analysis (RDA) plot highlighting the relationship between measured significant environmental variables with macroinvertebrate communities between the cool-dry and hot-wet seasons across three reservoirs, namely Nandoni, Thathe and Albasini. Abbreviations: Temp: temperature; Cond: conductivity; TDS: total dissolved solids: ORP: oxidation–reduction potential: T: Thathe; A: Albasini; N: Nandoni. The numbers correspond to: 1 = cool-dry; 2 = hot-wet. Abbreviations: Chironom: Chironomidae; Aeshnida: Aeshnidae; Libellul: Libellulidae; Notonect: Notonectidae; Apheloch: Aphelocheiridae; Gomphida: Gomphidae; Lymnaeid: Lymnaeidae; Hydroptl: Hydroptilidae; Gyrinida: Gyrinidae; Thiarida: Thiaridae; Corixida: Corixidae; Dytiscid: Dytiscidae; Coenagri: Coenagrionidae; Belostom: Belostomatidae; Potamon: Potamonautidae. (**b**) Redundancy analysis (RDA) plot highlighting the relationship between measured significant environmental variables with fish communities between the cool-dry and hot-wet seasons across three reservoirs, namely Nandoni, Thathe and Albasini. Abbreviations: Temp: temperature; Cond: conductivity; Mg: magnesium; ORP: oxidation–reduction potential: T: Thathe; A: Albasini; N: Nandoni; CLG: *Clarias gariepinus*; COR: *Coptodon rendalli*; ENA: *Enteromius afrohamiltoni*; ENP: *Enteromius paludinosus*; ENU: *Enteromius unitaeniatus*; GAA: *Gambusia affinis*; GLG: *Glossogobius guiris*; LAC: *Labeo cylindricus*; LAR: *Labeo rosae*; MEB: *Mesobola brevianalis*; MID: *Micropterus dolomieu*; MIS: *Micropterus salmoides*; ORM: *Oreochromis mossambicus*; TIS: *Tilapia sparrmanii*.

Table 5. Correlation coefficients between environmental variables and the first two axes of RDA ordination.

Figure 2a	**Axis 1**	**Axis 2**
Temperature	0.72	0.68
Conductivity	0.13	−0.99
ORP	−0.73	0.68
TDS	0.57	−0.82
Figure 2b		
Temperature	0.26	0.96
pH	0.52	0.85
ORP	0.51	0.77
Mg	−0.94	0.31
Conductivity	0.82	−0.56

4. Discussion

Understanding the dynamics of water quality, sediment chemistry and macroinvertebrate diversity indices is crucial for monitoring and assessing the health of aquatic ecosystems. Benthic macroinvertebrates and various fish species are some of the effective tools for evaluating the ecological state of aquatic environments [43,44]. Macroinvertebrates (21 taxa) and fish species (14 taxa) recorded in the three reservoirs over a period of two seasons demonstrated a relatively similar taxa richness when compared to other large reservoirs studies in other regions such as 32 macroinvertebrates taxa found in small reservoirs in the district [8]. Results of the present study show that macroinvertebrate and fish community diversity tended to change between seasons and associated changes in the physicochemical water quality variables. Littoral macroinvertebrates and fish were mainly driven by water quality variables, with only sediment Mg showing a significant association with fish assemblages. These results are similar to that of a study by Kolpin et al. [45] and Mofu et al. [46], which indicated that water quality variables can strongly structure fish assemblages.

From the present study, the Hemiptera order was dominant, followed by Odonata and Coleoptera, and these are among the most diverse aquatic insect orders that characterize almost all environmental conditions (from extremely pristine to degraded ecological conditions) [47]. One of the most significant and prevalent families of aquatic insects is the family Chironomidae, which belongs to the Diptera order. Its presence in any environment can serve as an indication of contamination [48]. Hence, in this study, high to low diversity of species within studied reservoirs (reservoirs situated in high catchment area to low catchment area) suggested that habitat conditions deteriorate from upstream to downstream. In this study, macroinvertebrate abundance decreases with season (cool-dry), which is not significant compared to those observed by Trottier et al. [49]. Therefore, there is still a lot of unanswered questions regarding the ecological processes involved and the direct and indirect causes of these ecosystem changes.

Throughout the study sites in all three reservoirs, we observed a high concentration in some water and sediment variables, suggesting that there may be various land uses activities within the catchment providing contaminants to these aquatic systems. Through field observation, most land adjacent to Albasini dam is dominated by commercial agriculture, which may be the primary contributors of nutrients to this reservoir. Furthermore, with an increase in land use activities adjacent to this reservoir, we predicted the decline in water and sediment quality at Albasini and Thathe in the near future. Looking at the Nandoni reservoir, water and sediment quality decline is associated with the various activities such as sewage treatment works, landfill site, recreation, fishing, washing in the reservoir, bathing, and ritual activities. The decline in water and sediment quality in aquatic environments can lead to a decline in absolute abundance, species richness and diversity, which can later result in declines in aquatic biodiversity [50]. Similarly, results of the present study agree with others that have demonstrated human activities changes to potentially change environmental variables in aquatic systems [51–53]. Therefore, understanding human activities in the watershed is crucial for the sustainable management of the aquatic environment.

The RDA suggests that some macroinvertebrate taxa such as Chironomidae, Gerridae, Dytiscidae, Gomphidae, Belostomatidae and Libellulidae were mostly affected by water variables (i.e., water temperature, ORP, TDS, and conductivity), with no sediment variable inducing any significant changes. Similarly, results were observed in other studies, where physicochemical parameters such as pH, conductivity and temperature drive macroinvertebrates communities [11,54,55]. Furthermore, fish communities within the three reservoirs in the study sites and across the two seasons were driven by water temperature, ORP, pH, and conductivity with an addition of sediment metal magnesium. According to Sylvain et al. [56], metals such as magnesium have been documented to drive microbiota and fish compositional shifts along widespread hydrochemical gradients. The high magnesium concentration in sediment was recorded in the littoral zones where fish sampling was performed, suggesting a direct influence of Mg on fish structure. However, we observed some resistant fish species (*M. salmoides*, *O. mossambicus*, *C. rendalli* and *T. sparrmanii*) which were found in littoral zones of the Nandoni reservoir, which recorded a high concentration of sediment metals and physicochemical variables. Furthermore, significant changes in fish and macroinvertebrates diversity indices were observed, whereby species richness and Shannon wiener diversity decreased with water quality concentration across sites.

According to Zhang et al. [57], reservoirs with a substantial amount of anthropogenic activity input are likely to have higher sediment metal concentrations, which has major negative impacts on aquatic biota. Similarly, Tamiru [58] highlighted that in the lake Tana (Northwestern Ethiopia), changes in water chemistry had a considerable impact on aquatic biodiversity, leading to significant changes in biomass, productivity, and littoral biogeochemistry. Therefore, since species reacted to changes in environmental factors, these findings may suggest that fish species are the primary determinants of biotic community structure within reservoirs with exception to few variables. The results of the present study agree with the hypothesis that fish and macroinvertebrates community diversity will be high during the hot-wet seasons since most of these reservoirs increase water levels during the hot-wet season, which provides a conducive environment for fish and macroinvertebrates to thrive.

5. Conclusions

The present study indicates that the abundances and diversity of macroinvertebrates and fish taxa are driven by seasonal patterns in the littoral zones of subtropical reservoirs. In addition, selected water and sediment chemistry variables were able to drive the species assemblages within the reservoirs. Among the local environmental factors, sediment metal has little impact on the species communities as compared to water parameters, allowing only a narrow spectrum of sediment and water chemistry to drive the structure of macroinvertebrates and fish. Seasonal changes were shown to contribute highly to the communities based on diversity indices, which significantly changes across seasons. These findings suggest that management strategies aimed at maintaining high levels of aquatic biodiversity in reservoirs should be directed towards reducing the level of anthropogenic pressure (i.e., contaminants from the catchment, including those in water and benthic sediments), while ensuring the continuous assessment of aquatic fauna to determine the ecological status.

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