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# Evaluation of aquatic ecosystem health via benthic macroinvertebrates and physicochemical parameters in the northern Sahara, Algeria

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This study aims to assess the ecological integrity of water habitats in the northern Sahara of Algeria, utilizing a multiparametric approach focused on the ecology of benthic macroinvertebrates. To monitor the water quality, benthic macroinvertebrates and physicochemical parameters were analyzed monthly from August 2015 to November 2017 throughout five aquatic ecosystems: Z'mor wadi, Ithel wadi, Djedi wadi, Ayata lake, and Megarine lake. The physicochemical analysis results indicate that the pH values at the research sites ranged from mildly alkaline to alkaline. Turbidity and suspended solids were markedly increased in Djedi wadi and Z'mor wadi. The mean $BOD_5$ values across all examined aquatic systems demonstrated moderate organic pollution levels, with the highest amounts recorded in Djedi wadi, Ithel wadi, and Megarine lake. In terms of salinity, Djedi wadi exhibited slightly brackish conditions, whereas the remaining sites ranged from brackish to highly brackish. The recorded fauna included 995 individuals, representing 55 genera/taxa across 8 orders and 29 families. The most diverse taxa were Coleoptera (24 taxa), Diptera (14 taxa), and Hemiptera (10 taxa), with Diptera and Coleoptera being the most dominant. Z'mor and Ithel wadis had the highest biodiversity, with a total richness of 35 taxa and a Shannon score over 2.50. PCA-Biblot and cluster analysis identified three groups, indicating the significance of site typology and environmental factors for the distribution of benthic macroinvertebrate communities. The IBGN evaluation classified the hydrobiological quality of water as poor (IBGN score of 5) in Djedi wadi, Ithel wadi, Megarine lake, and Ayata lake, but Z'mor wadi demonstrated moderate water quality with an IBGN score of 9.

*Keywords*: benthic macrofauna; physicochemical parameters; diversity indices; Northern Sahara; Algeria.

## Introduction

Aquatic ecosystems are dynamic and complex, functioning as vital components of the landscape due to their significant biological productivity, rich biodiversity, and the various ecological processes and services they support (Higler, 2009). These habitats are essential for maintaining biodiversity, facilitating the functioning of diverse organisms, and contributing to the organic matter cycle (Dynesius & Nilsson, 1994). Arid zones, which include more than one-third of the Earth's terrestrial area, are characterized by low and irregular precipitation, yet frequently contain a surprising variety of aquatic ecosystems (Jenkins et al., 2005). Water availability is a crucial determinant of the ecology in arid and semi-arid landscapes (Stafford Smith & Morton, 1990), with rivers and their flow patterns playing a substantial role in ecological variability in these regions (Walker et al., 1995).

Macroinvertebrates, such as insects, function as reliable bioindicators owing to their restricted movement, considerable diversity, and differing tolerance to pollution and habitat degradation (Moisan & Pelletier, 2008). Bioindication refers to the ability of species or communities to signify environmental attributes and alterations through their presence, absence, or demographic reactions (Blandin, 1986). These entities are designated as bioindicators. Biological monitoring offers a cost-efficient method for evaluating environmental conditions compared to chemical tests, especially in identifying the degradation of aquatic habitats and the reduction of biodiversity due to human activities (Hynes, 1960; Hawkes, 1979; Karr, 2000). Macroinvertebrates constitute a highly varied taxonomic group that includes various phyla.

The considerable morphological variation within this group facilitates a broad spectrum of reactions to environmental disturbances, rendering them prime candidates for bioassessment (Rosenberg & Resh, 1993). Benthic macroinvertebrates are essential to numerous biotic indices, predominantly depending on the abundance or diversity of particular indicator taxonomic groups (Rosenberg & Resh, 1993; Tachet et al., 2006). These creatures provide a comprehensive depiction of ecological integrity (Yoder & Rankin, 1995). Currently, the biological monitoring of benthic populations serves as the most sensitive instrument for the rapid and precise detection of perturbations in aquatic ecosystems (Cairns & Pratt, 1993).

In North Africa, rivers (wadis) display varied physical conditions, characterized by severe floods and drought occurrences (Pires et al., 1999), as well as erratic flow patterns and significant hydrological variability (Giudicelli et al., 1985). In Algeria, especially in the Northern Sahara, continental aquatic environments are prevalent and sustain significant richness in both flora and fauna. These fragile aquatic ecosystems encompass wadis, lakes, dams, hill reservoirs, chotts, and sebkhas, exhibiting water salinity levels that vary from fresh to brackish, saline, or hypersaline (Gauthier, 1982; Ballais, 2010).

Research on benthic macroinvertebrates and their habitats in the Northern Sahara is scarce, characterized by a small number of fragmented and ad hoc investigations. Despite the critical ecological functions and socio-economic services offered by aquatic habitats, especially in the expansive Northern Sahara, their structural and organizational characteristics are inadequately recorded. This disparity is particularly pronounced regarding the diversity of communities, both in terms of species and functional functions adapted to these extreme climatic conditions (Ghazi et al., 2019).

The objective of this study is to assess the physicochemical condition of aquatic habitats across the northern Sahara, employing both in situ and laboratory analyses. Additionally, it seeks to enhance taxonomic knowledge of benthic macroinvertebrates and to evaluate the biological quality and ecological integrity of aquatic ecosystems throughout the region.

## Materials and methods

*Characterization of the study region and the examined aquatic ecosystems.* A thorough sampling was executed from 2015 to 2017 across five unique continental aquatic ecosystems characterized by brackish to salt water conditions. The sites, located over four wilayas in the northeastern and eastern sectors of the Algerian Sahara, comprise Z'mor wadi, Djedi wadi, Ithel wadi, Ayata lake, and Megarine lake (Fig. 1, Table 1). These habitats are located within five principal watersheds: Saharan, El Hodna, Medjerda Basin, Highlands, and Chott Melghir (Chaibi et al., 2012).

All examined sites function as drainage and urban wastewater exits for the palm groves farmed in the region (Côte, 2006). The examined sites, situated within the Saharan bioclimatic stage, exhibit significant floristic biodiversity, with 480 species, of which 162 are endemic (Quézel, 1978). The various inventories conducted in this region documented 78 bird species, predominantly waterfowl (Chenchouni, 2012; Bensaci et al., 2013), 20 mammal species, and 35 reptile species (Mouane, 2010), along with an ichthyological assemblage comprising 7 species, representing over 10% of the Algerian continental ichthyofauna (Toumi, 2010; Chaibi et al., 2013; Ghazi & Si bachir, 2021).

Mainly comprising: pebbles, boulders, sand, solid supports, and aquatic vegetation, Z'mor wadi displayed the greatest substrate diversity, whereas Djedi wadi consisted exclusively of sand. Additionally, benthic macroinvertebrates were predominantly gathered from vegetation at Itehl wadi, Ayata and Megarine lake that consisted mostly of sand and plants (Table 1).

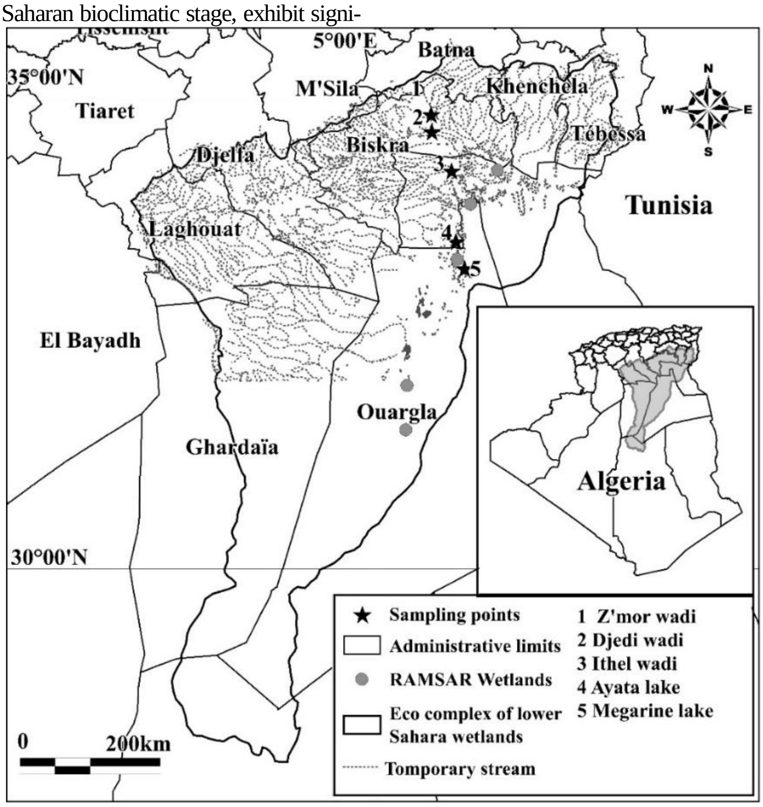


**Fig. 1.** General hydrographic network of the surveyed area with the location of the five study sites in the northern Sahara, Algeria

**Table 1**
Details of sites sampled during the study (Alt: Altitude; N: Benthic macroinvertebrate sampling number; S: salt)

| Site | Code | Elvation, m | Latitude / longitude | Type | Substrates | Mean depth, m | N |
|---|---|---|---|---|---|---|---|
| Z'mor Wadi | B | 94 | 34° 50' 51'' N 05° 40' 52'' E | lotic | sand, pebble, boulder, and vegetation | 0.50 | 11 |
| Djedi Wadi | D | 45 | 34° 39' 45'' N 05° 41' 31'' E | lotic | pebbel and vegetation | 2.50 | 23 |
| Ithel Wadi | ST | 7 | 34° 14' 53'' N 05° 55' 08'' E | lotic | sand | 1.00 | 23 |
| Ayata Lake | A | 40 | 33° 29' 17'' N 05° 59' 10'' E | lentic | sand and vegetation | 0.75 | 23 |
| Megarine Lake | M | 76 | 33° 12' 24'' N 06° 05' 53'' E | lentic | sand, and vegetation | 3.20 | 23 |

*Environmental attributes and water assessment.* Monthly sampling was undertaken at the five sites from August 2015 through September 2017. At the Algerian Water Laboratory (ADE – Batna), 12 parameters characterizing water quality were analyzed periodically. These were pH, turbidity (Nephelometric Turbidity Unit, NTU), conductivity (µS/cm), salinity (‰); the concentration of total dissolved solid elements TDS (mg/L), as well as the dosage of the following elements: $Ca^{+2}$, $Mg^{+2}$, $NO_3^-$, $SO_4$, $NO_2^-$, $NH_4^+$, and $PO_4^{-3}$ (mg/L). Two pollution parameters were measured at the ONA laboratory – Batna, with the aim of evaluating the degree of pollution of the prospected sites. For the period from October 2016 to October 2017, the Biological Oxygen Demand (BOD5) was measured twice/sites/period (hot and cold), while the chemical oxygen demand (COD) was measured throughout the period with a monthly frequency. The samples from the water examined were those already used when determining the physicochemical quality of the water. The aquatic ecosystems' substrates were categorized into four types: (i) fine sand (diameter < 2 mm); (ii) coarse sand (2–25 mm); (iii) stones (25–250 mm); and (iv) boulders (> 250 mm; Tachet et al., 2010), with their percentage cover evaluated visually (Touron-Poncet et al., 2014).

*Sampling of benthic macroinvertebrates.* Benthic macroinvertebrates were collected from diverse habitat compartments (substrates) from August 2015 to November 2017, using a Surber net (500 µm mesh size, 0.20 m² area; Touron-Poncet et al., 2014). The collected samples were preserved in plastic containers with 4% formalin (Tachet et al., 2010). The identification of macroinvertebrates was carried out with the highest possible level of precision, based on the identification keys proposed by Tachet et al. (2010).

For each benthic macroinvertebrate family, the abundance frequency ratio (AF%) was calculated as the percentage of the number of individuals in a given family relative to the total number of individuals across all families. For each benthic macroinvertebrate community, we calculated the total taxonomic richness (S), the Shannon-Weaver diversity index (H') using the formula ($H' = -\Sigma p_i \times \log_2 p_i$) and

Pielou's evenness index (J'), where $J' = H'/H_{max}$, and $H_{max} = \log_2 S$ (Magurran, 2004).

*Statistical analysis.* A principal component analysis (PCA) was conducted to examine the environmental and ecological associations between aquatic macroinvertebrate groups and sampling sites, supplemented by hierarchical clustering (CAH) using Euclidean distance and "complete linkage" as aggregation criteria. A heatmap was generated to illustrate the distribution of abundance frequency of macroinvertebrate orders and families among sampling sites.

The variations between different wadis in terms of Shannon's diversity index and the pH parameter were assessed through one-way ANOVAs. When significant effects were observed ($P \leq 0.05$), Newman-Keuls post-hoc tests were employed to identify specific differences between groups. In cases where normality assumptions were not met, particularly for variables like taxa richness, the Pielou index and other physicochemical parameters (conductivity, turbidity, temperature, TDS, BOD5, COD, nitrate ($NO_3^-$), nitrite ($NO_2^-$), and orthophosphate ($PO_4^{-3}$)), comparisons between wadis were carried out using the Kruskal-Wallis test.

The IBGN index is based on benthic macroinvertebrate communities. These are placed relatively high in the scale of complexity of aquatic organisms. In addition, their nutritional modes are diversified, which allows them to colonize all types of habitats. Their integrating power of aquatic environment dysfunctions is therefore very strong. These considerations make the IBGN the most globalizing index of the freshwater aquatic ecosystem. It will therefore reveal a general quality of the watercourse by integrating the habitat potential. The principle of this method is based on the sampling of benthic macrofauna at a station, according to a standardized sampling method, taking into account the different types of habitats (Genin et al., 2003).

After laboratory classification of macroinvertebrates and compilation of the faunal inventory, the following parameters were determined (Table 2): taxonomic diversity (Σt), defined as the total count of identified taxa, independent of the number of individuals within each taxon. The faunal indicator group (F.I.G.) represents the most "pollution-sensitive" taxon, which is the indicator taxon with a significant presence at the site (at least 3 or 10 individuals depending on the taxa) and the highest possible sensitivity index. The IBGN (French Biological Quality Index) is subsequently calculated using a two-way analysis table: on the x-axis, taxonomic quality classes (from 1 to 14), and on the y-axis, indicator groups (IG) ranked in descending order of pollution sensitivity (from index 9 to index 1).

**Table 2**
Grid assessment for water quality (AFNOR, 1992) IBGN: Global Standardized Biological Index

| IBGN | ≥ 17 | 13–16 | 9–12 | 5–8 | 4 |
|---|---|---|---|---|---|
| Class quality | 1A | 1B | 2 | 3 | HC* |
| Matching colour | blue | green | yellow | orange | red |
| Hydrobiological quality | verry good | good | medium | poor | bad |

*Note*: HC* – out of class.

## Results

*Environmental parameters.* The water temperature exhibited no statistically significant difference across the study sites ($P > 0.05$). The minimum temperatures at the prospected locations varied from 10.5 °C at Ayata lake to 7 °C at Ithel wadi, whilst the maximum temperatures ranged from 33 °C at Z'mor wadi to 46.9 °C at Djedi wadi. At the latter location, the inter-monthly fluctuation was maximal, with a standard deviation of ±11.3 °C, whereas the minimal variation was recorded at Z'mor wadi, with a standard deviation of ±7.65 °C.

The analysis of pH fluctuations at the study locations revealed that the observed pH averages varied from 7.8 to 8.4. The highest average was recorded at Z'mor wadi, whilst Ithel wadi, Ayata lake, and Megarine lake displayed the lowest average. This variance is statistically significant ($P < 0.0001$; Fig. 2).

The spatial variation of salinity exhibited a significant difference across the sites ($P < 0.0001$; Fig. 2). Ayata lake and Djedi wadi exhibited the lowest values among the other sites, with averages of 3.53‰ and 7.24‰. Conversely, at Z'mor wadi, Ithel wadi, and Megarine lake, the salinity averages continuously exceeded 12.7‰.

The water turbidity exhibited considerable variation across several sites ($P < 0.0001$; Fig. 2).

The readings were significantly lower at Ithel wadi, Ayata lake, and Megarine lake, with averages of 5.52, 4.15, and 3.56 NTU. Conversely, the measurements at Djedi wadi and Z'mor wadi surpassed 9.5 NTU, varying between 9.89 and 16 NTU.

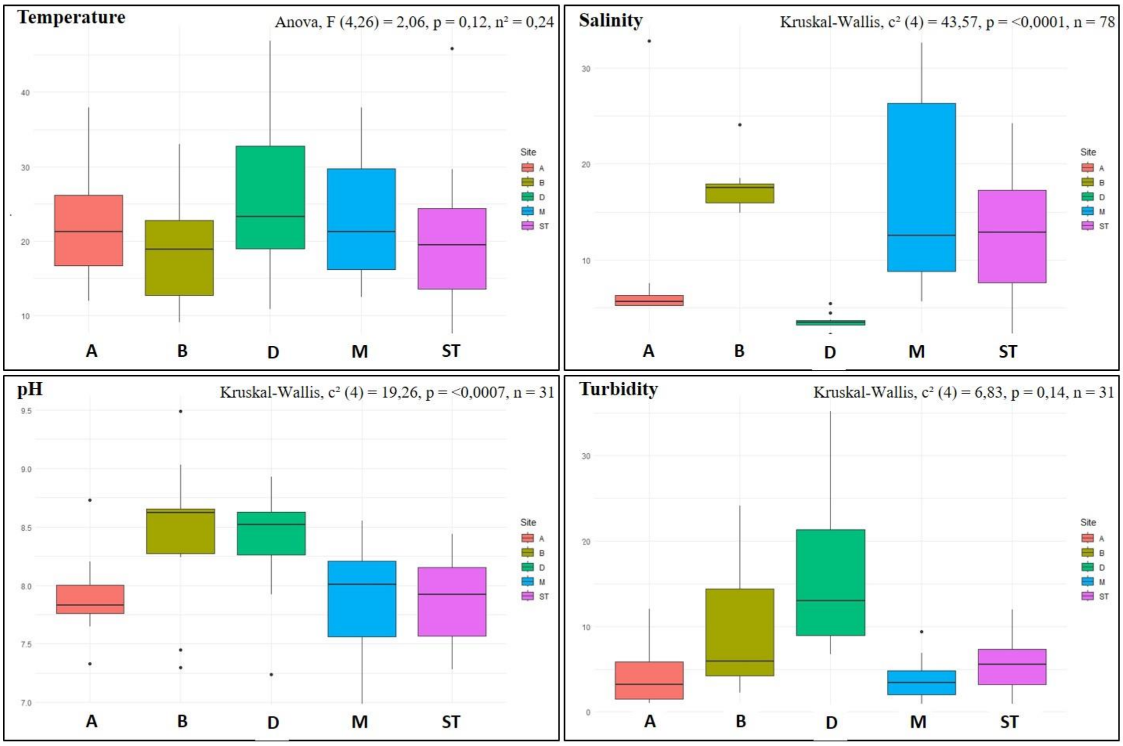


**Fig. 2.** Boxplot showing the variation of temperature, pH, salinity and turbidity variables and results of the Kruskal-Wallis test for sampling sites in the northern Sahara, Algeria: W.B –Z'mor Wadi; W.D – Djedi Wadi; W.ST – Ithel Wadi; A – Ayata Lake; M – Megarine Lake

The variation in Chemical Oxygen Demand (COD) among locations was significantly evident. The average COD concentrations exceeded 160 mg/L in both Ithel wadi and Megarine lake, although Z'mor wadi displayed a lower mean value of 90.6 mg/L (Fig. 3). Conversely, COD concentrations varied from 56 to 60 mg/L in Djedi wadi and Ayata lake. Statistically significant differences in COD levels were identified between Djedi and Ithel wadis ($P < 0.01$), with significantly elevated values noted at Ithel wadi (Fig. 3). Biochemical oxygen demand (BOD5) regularly stayed below 9 mg/L in Megarine lake and Z'mor wadi. In Ithel wadi, the average BOD5 values were roughly 12.6 mg/L. Conversely, Ayata lake and Djedi wadi demonstrated heightened BOD5 levels, surpassing 18 mg/L (Fig. 3). The results indicated that the mean concentrations of $NO_2^-$, $NH_4^+$, and $PO_4^{-3}$ were predominantly low at the sites, consistently remaining under 2 mg/L. Elevated mean concentrations of $NO_2^-$ and $NH_4^+$ were recorded in Djedi wadi and Ayata lake relative to other sites. Peak concentrations of $NO_2^-$ and $NH_4$ were also recorded at these two sites. The results showed that only $NO_2^-$ and $NH_{4+}$ concentrations varied significantly among the sites (Fig. 3).

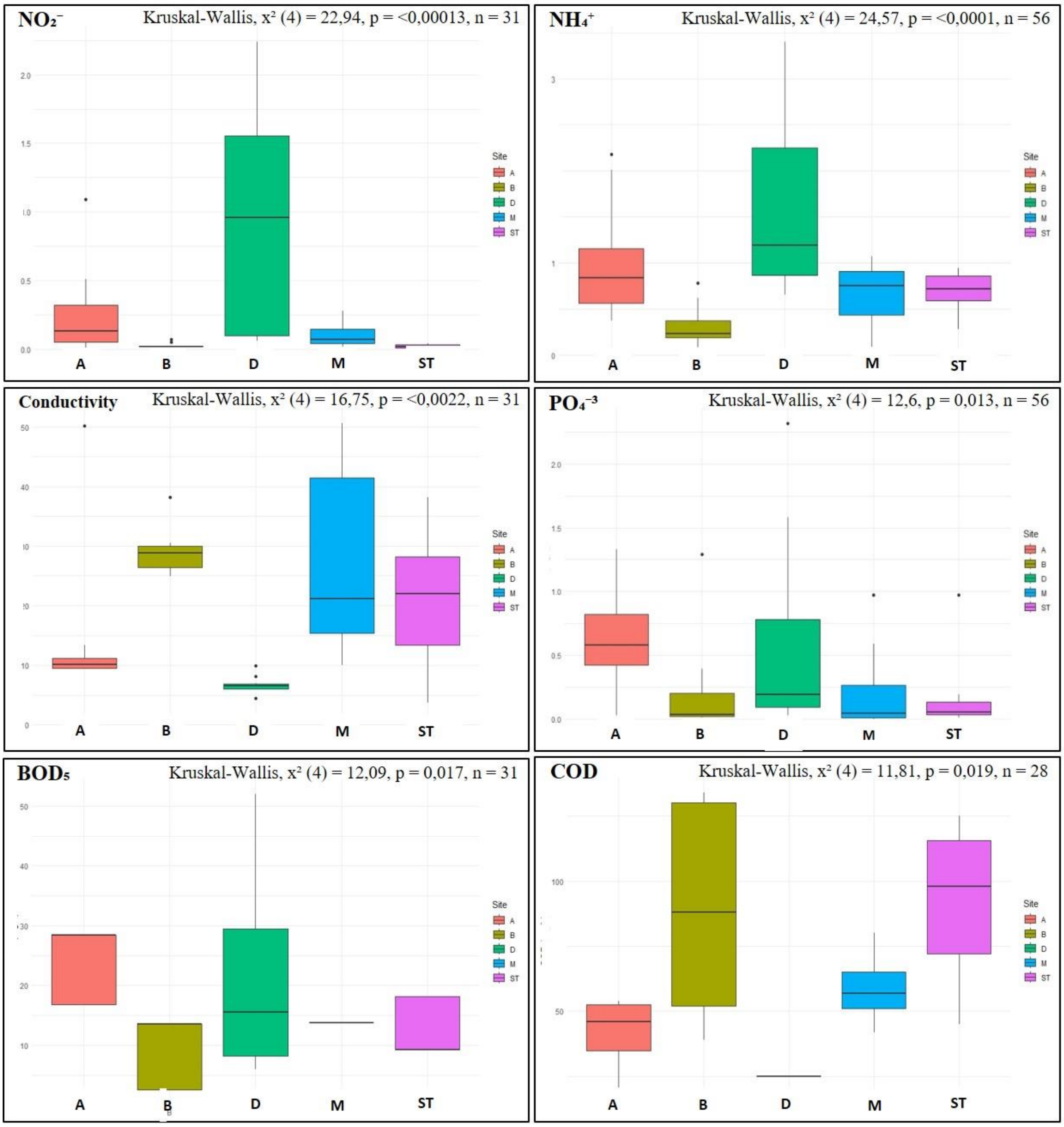


**Fig. 3.** Boxplot showing the variation of conductivity, $NO_2^-$, $NH_4^+$, $PO_4^{-3}$, BOD5 and COD variables and results of the Kruskal-Wallis test for sampling sites in the northern Sahara, Algeria: W.B – Z'mor Wadi; W.D – Djedi Wadi; W.ST – Ithel Wadi; A – Ayata Lake; M – Megarine Lake

*Diversity and distribution of macroinvertebrates communities.* A total of 995 individuals were collected, encompassing 55 genera / species across 8 orders and 29 families. Diptera was the most abundant group, representing 49.8% of the total abundance, which included 12 genera / species across 11 families (Table 3).

Coleoptera exhibits consistently high abundance across all sites, notably at Ithel wadi, Z'mor wadi and Ayata Lake, Diptera were particularly prevalent at Z'mor wadi and Ithel Wadi. Odonata and Hemiptera exhibit greater abundance in Djedi Wadi. Certain taxa, such as Gastroopoda and Podocopida have erratic distribution and occur at low abundance (Fig. 4B).

The most abundant families were Hydrophilidae (39.73% of total abundance), Dytiscidae (20.34%), and Corixidae (9.74%). Multiple families (Tabanidae, Simuliidae, Psychodidae) were observed at minimal abundance (Fig. 5A). The Hydrophilidae family was mostly located in Z'mor wadi, Ithel wadi, and Ayata lake. The Dytiscidae family was notably prevalent in the Z'mor wadi and Ithel wadi sites. Corixidae primarily resided within the aquatic insect populations of

Ithel wadi and Djedi wadi, while also demonstrating a significant presence at Megarine lake (Fig. 5B).

**Table 3**
List of benthic macroinvertebrates collected among sampling sites in the Northern Sahara, Algeria

| Phylum | Class | Order | Family | Taxa |
|---|---|---|---|---|
| Mollusca | Gastropoda | Pulmonata | Lymnaeidae | *Galba trancatula* |
| | Crustacea | Amphipoda | Gammaridae | *Gammarus* sp. |
| Arthropoda | Insecta | Odonata | Coenagrionidae | *Ischnura* sp. |
| | | | | *Zygopetera* sp. |
| | | | Libellulidae | *Orthetrum* sp. |
| | | | | *Lebellula* sp. |
| | | | Aeshnidae | *Anax* sp. |
| | | Ephemeroptera | Baetidae | *Procloeon* sp. |
| | | | | *Baetis* sp. |
| | | | | *Cloeon* sp. |
| | | | Siphlonuridae | *Siphlonerus* sp. |
| | | Coleoptera | Dytiscidae | *Agabus* sp. |
| | | | | *Dytiscus* sp. |
| | | | | *Neberioporus* sp. |
| | | | | *Neberioporus baeticus* |
| | | | | *Yola* sp. |
| | | | | *Deronectes* sp. |
| | | | | *Eretes* sp. |
| | | | | *Oreodytes* sp. |
| | | | | *Bidessus* sp. |
| | | | Haliplidae | *Halipilus* sp. |
| | | | Hydraenidae | *Octhebius* sp. |
| | | | | *Hydraena* sp. |
| | | | Hydrophilidae | *Anacaena* sp. |
| | | | | *Berossus* sp. |
| | | | | *Chaetarthria* sp. |
| | | | | *Crenitis* sp. |
| | | | | *Cymbiodyta* sp. |
| | | | | *Enochrus* sp. |
| | | | | *Helochares* sp. |
| | | | | *Hydrophilus pistaceus* |
| | | | | *Laccobius* sp. |
| | | | | *Ecdynorus* sp. |
| | | | | *Paracymus* sp. |
| | | | Noteridae | *Noterus* sp. |
| | | Diptera | Chironomidae | *Chironomus* sp. |
| | | | Ephydridae | *Ephydridae* sp. |
| | | | Psychodidae | *Psychodidae* sp. |
| | | | Dolichopodidae | *Dolichopodidae* sp. |
| | | | Ptychopteridae | *Ptychopteridae* sp. |
| | | | Simulidae | *Simulidae* sp. |
| | | | Stratiomydae | *Stratiomydae sp* |
| | | | Hypatgénidae | *Hypatgénidae* sp. |
| | | | Syrphidae | *Syrphidae* sp. |
| | | | Culicidae | *Culex* sp. |
| | | | Tabanidae | *Tabanidae* sp. |
| | | | Muscidae | *Limnophera* sp. |
| | | Hemiptera | Corixidae | *Arctocorisa* sp. |
| | | | | *Sigara* sp. |
| | | | | *Corixa* sp. |
| | | | | *Corixidae* sp. |
| | | | Veliidae | *Veliidae* sp. |
| | | | Micronectidae | *Micronecta* sp. |
| | | | | *Micronotonecta* sp. |
| | | | Notonectidae | *Notonecta* sp. |
| | Ostracoda | Podocopida | Cyprididae | *Eucypris* sp. |

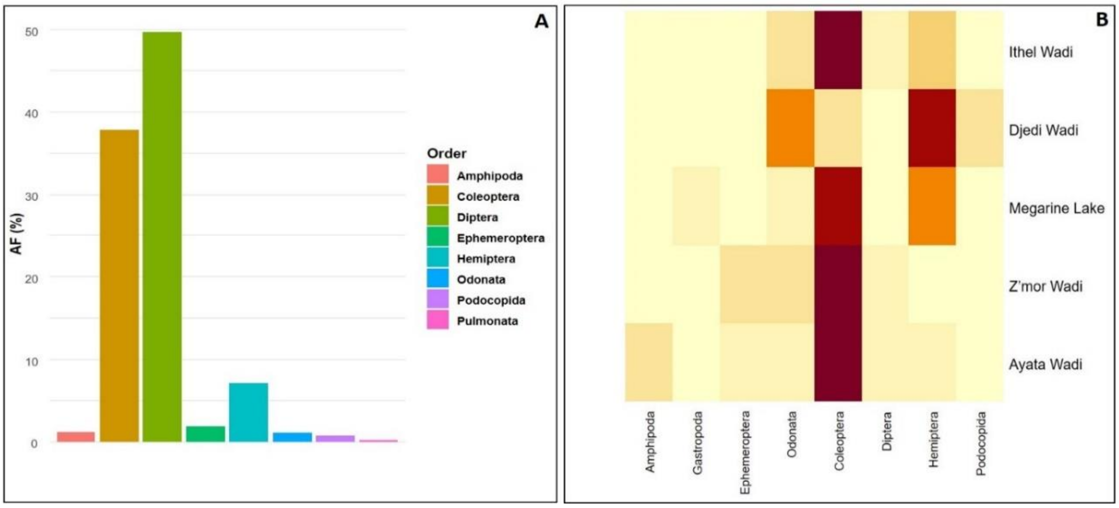


**Fig. 4.** Abundance frequency (AF %) of macroinvertebrate orders collected across all study sites (A); heatmap showing the distribution of macroinvertebrate orders between sampling sites (B): colour gradient reflects the abundance frequency, with darker hues indicating higher values)

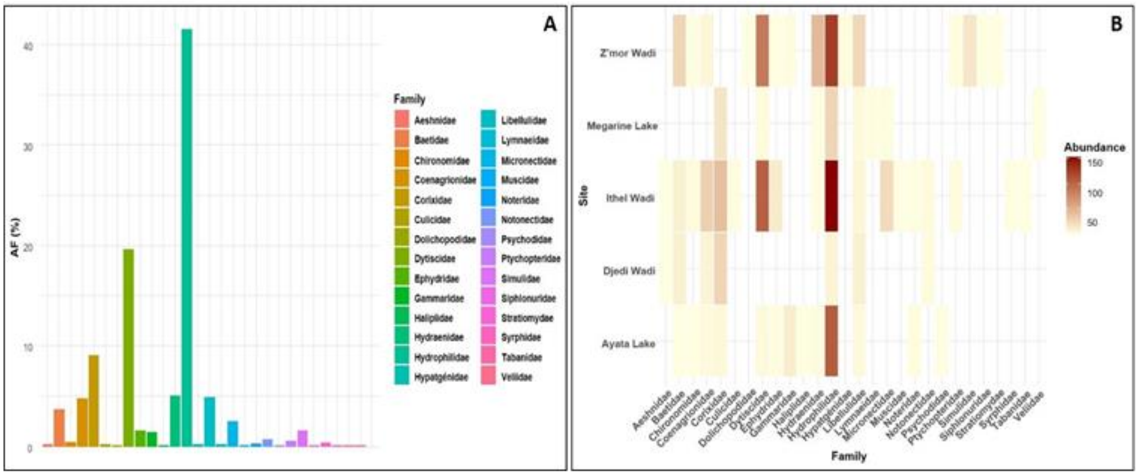


**Fig. 5.** Abundance frequency (AF %) of macroinvertebrate families collected across all study sites (A); Heatmap showing the distribution of macroinvertebrate families between sampling sites (B): colour gradient reflects abundance frequency, with darker hues indicating higher values

The first two principal components (Dim1 and Dim2) of the physicochemical parameters analysis, accounted for 48.8% and 31.2% of the total variance, respectively, yielding a combined total of 80% of the dataset's variability. Dim1 was mostly affected by physicochemical characteristics such as conductivity, salinity, elevation, and mean depth, which showed positive loading, whereas temperature, $NO_2$, and $BOD_5$ exhibited negative loading. Dim2 had a moderate correlation with pH and turbidity (Fig. 6A). Z'mor wadi and Megarine lake demonstrated elevated salinity, conductivity, and altitude, but Djedi wadi was closely associated with temperature and $NO_2$ levels. Ayata lake demonstrates a strong association with $BOD_5$ (Fig. 6A). The hierarchical clustering dendrogram confirms the classification of the sites based on environmental characteristics, aligning with the patterns shown in the PCA (Fig. 6B).

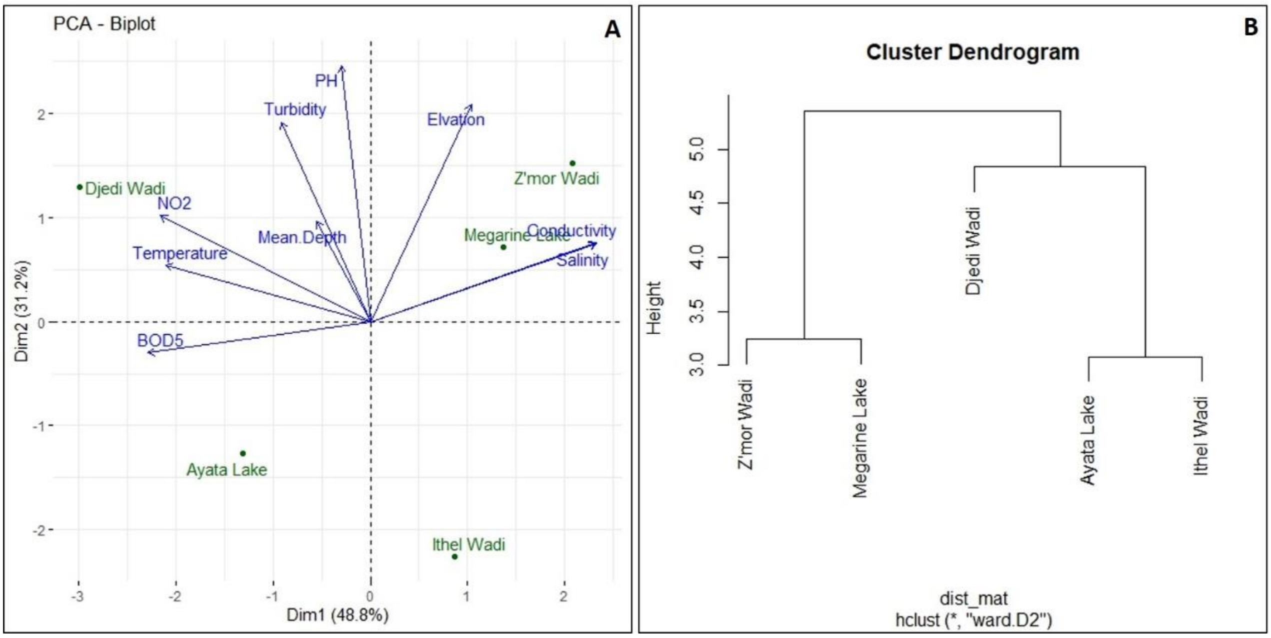


**Fig. 6.** Biplot of Principal Component Analysis (PCA) showing the correlation between environmental variables and sampling sites (A); the hierarchical clustering dendrogram further corroborates the PCA (B) by categorizing sites according to environmental similarities

The principal components, Dim1 (45.6%) and Dim2 (30.7%), of the aquatic invertebrate families demonstrate the correlations between the sampling sites and invertebrate families, collectively accounting for 76.3% of the total variation in the sample. Z'mor wadi was isolated and linked to Hydridae, Simuliidae, Libellulidae, among others, indicating a distinctive community structure. Ithel wadi exhibited a significant prevalence of Chironomidae, Syrphidae, and Coenagrionidae. Djedi wadi, Megarine lake, and Ayata lake were clustered together, associated with Lymnaeidae, Psychodidae, Haliplidae, and others (Fig. 7A). The dendrogram clusters of invertebrate families emphasize two primary branches. Hydrophilidae and Corixidae are included, suggesting common ecological traits or habitat affinities. The other major branch diverges into more precisely delineated groupings, distinguishing families such as Chironomidae, Psychodidae, and Muscidae from others including Simuliidae, Aeshnidae, and Dolichopodidae (Fig. 7B).

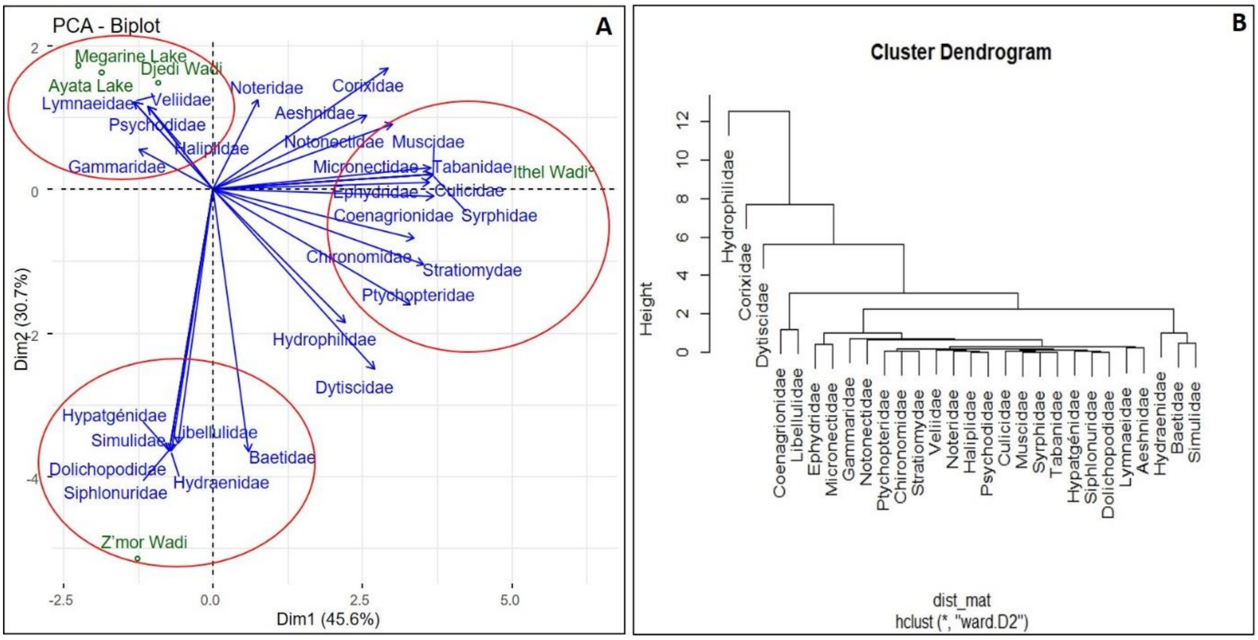


**Fig. 7.** Biplot of Principal Component Analysis (PCA) showing the correlation between aquatic invertebrate families and sampling sites (A), the hierarchical clustering dendrogram further validates the PCA by classifying sites based on similarities in family compositions (B)

Only taxonomic richness (S) and the Shannon index (H') differed significantly between sampling sites, with higher S scores recorded at Z'mor wadi compared to Djedi wadi and L. Megarine ($p < 0.001$; Fig. 5). The highest H' was also observed at Z'mor wadi compared to Megarine lake ($P < 0.01$; Fig. 8). No significant difference in Pielou's evenness index (J') was recorded between sampling sites ($P > 0.05$).

*Evaluation of the standardized global biological index (IBGN).* The hydrobiological quality of the water in the five studied sites is qualified as:

1. Poor (IBGN between 5, Class quality 2), combining a low taxonomic variety (Table 4).

2. Medium (IBGN between 9, Class quality 2), combining a low taxonomic variety (Table 4).

**Table 4**
Assessment grid of the water quality of the 5 studied sites in northern Sahara, Algeria (W.B – Wadi Z'mor; W.D – W. Djedi; W.S – W. Ithel; L.A – Ayata Lake; L.M – L. Megarine; IBGN: Global Standardized Biological Index)

| Sites | Variety class | IG | IBGN value | Class quality | Water quality |
|---|---|---|---|---|---|
| W. B | 8 | 2 | 9 | 2 | medium |
| W. S | 4 | 2 | 5 | 3 | poor |
| W. D | 4 | 2 | 5 | 3 | poor |
| L. A | 4 | 2 | 5 | 3 | poor |
| L. M | 4 | 2 | 5 | 3 | poor |

## Discussion

This study provides a preliminary analysis of the composition of benthic macroinvertebrate communities in the aquatic habitats of the vast Northern Sahara region, emphasizing significant environmental factors that may affect their structure.

The findings of the spatial pH variation demonstrate that the studied hydro-systems range from mildly alkaline to alkaline. Based on the scale established by Hecker et al. (1996), a pH exceeding 7.4 indicates that the disparity in average pH between lotic and lentic water systems can be attributed to the biological activity. The elevated turbidity and substantial concentration of suspended particles in the Djedi wadi can be attributed to its significance within the extensive watershed of the Chott Melghir, the primary collector of runoff water from a region of roughly 9,130 km² on the southern slope of the Saharan Atlas (Bouchemal, 2017). Furthermore, Z'mor wadi receives tributaries from four wadis (Zemmam, 2019). The average turbidity observed in the two examined lakes is similar to that reported by Hammouda (2013). Cataliotti Valdina (1982) asserts that wind can induce sediment resuspension, thereby elevating water turbidity. The maximum wind speed in our study area occurs from March to May and September to November (Lemkeddem & Telli, 2014), coinciding with reported floods, especially in the W. Djedi wadi and W. Z'mor.

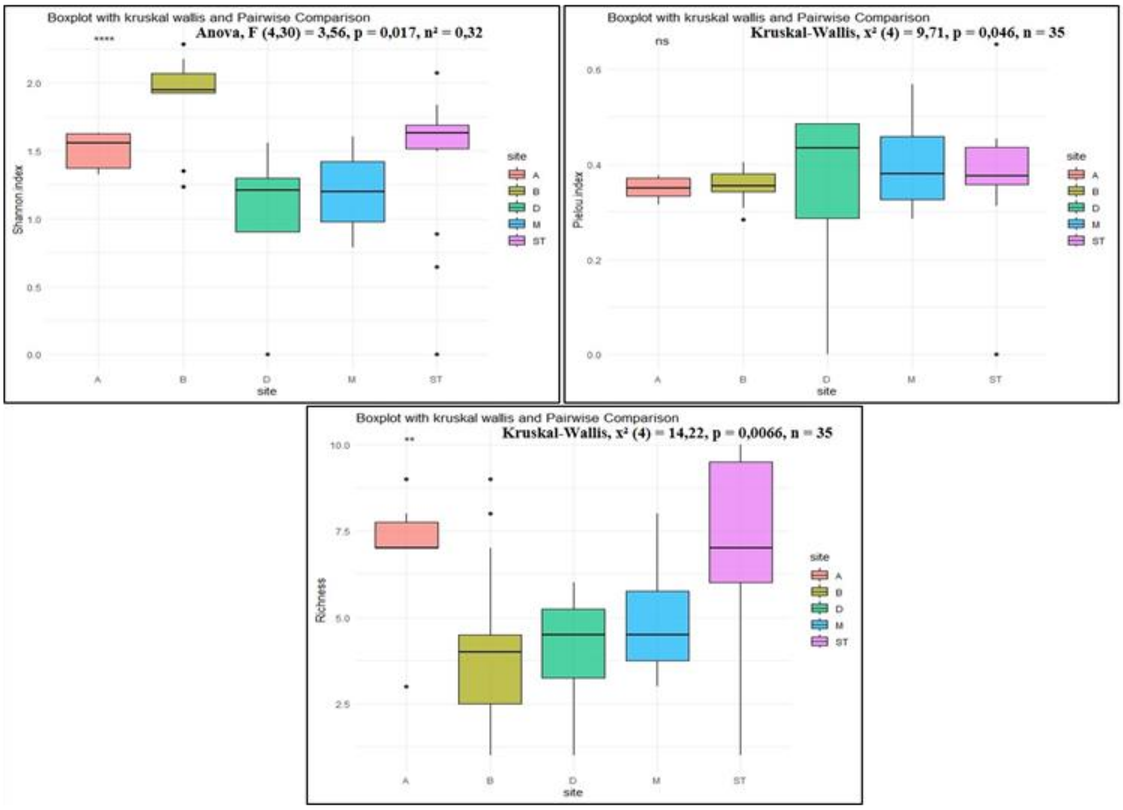


**Fig. 8.** Box-plots showing differences between sampling sites in terms of the taxa richness (S), Shannon diversity index (H') and Pielou index (J') of benthic entomofauna in septentrional Sahara, Algeria: W.B – Z'mor Wadi; W.D – Djedi Wadi; W.ST – Ithel Wadi; A – Ayata Lake; M – Megarine Lake

The average $BOD_5$ of all examined hydro-systems suggests that pollution levels in these systems range from moderate to considerable, as classified by Rodier (1996). Benameur (2018) documented analogous findings, indicating that the $BOD_5$ levels in W. Z'mor average between 10 and 15 mg/L. Furthermore, fluctuations in chemical and biological oxygen demand throughout time are affected by hydro-climatic and biological factors, including temperature, precipitation, salinity, photosynthetic activity, nitrates, and orthophosphates (Dufour, 1982; Villeneuve et al., 2006).

The inventory documented 55 benthic macroinvertebrate taxa, confirming the restricted qualitative and quantitative diversity noted in prior studies of North African wadis. These ecosystems, similar to other Mediterranean rivers, exhibit considerable hydrological fluctuation and harsh physical circumstances (Lounaci et al., 2000; Arab et al., 2004; Belaidi et al., 2004). Consequently, intermittent streams generally sustain a reduced number of species in comparison to permanent streams (Del Rosario & Resh, 2000). The taxonomic diversity seen in the Northern Sahara region of Algeria was inferior to that documented in more humid areas of Northern Algeria, characterized by greater annual precipitation, such as the Kabylie region (Lounaci, 2005) or the Soummam River (Zouggaghe & Moali, 2009).

The limited taxonomic diversity noted in many arid and semi-arid regions of Algeria (Bebba et al., 2015; Sellam et al., 2017; Ghougali et al., 2019) is attributable to fluctuating environmental circumstances. These encompass recurrent flow disruptions, inadequate water levels during flow periods, and elevated summer temperatures surpassing 35 °C, which intensify drought conditions and adversely affect biodiversity (Arab et al., 2004). This pattern seems to align with observations in intermittent rivers globally, including those in California, the Mediterranean Basin, Chile, South Africa, and southwestern Australia (Williams, 1996; Bonada, 2003).

Diptera emerged as the predominant taxon, aligning with observations from other arid Mediterranean streams in North Africa (Sellam et al., 2017; Ghougali et al., 2019). Pires et al. (2000) similarly identified Diptera as the predominant taxon in intermittent streams in Portugal, ascribed to their significant drought resilience and efficient recolonization mechanisms. Their larvae were notably prevalent, attaching to stable substrates like stones and boulders, presumably because of their filter-feeding behavior (Tachet et al., 2010) and their capacity to withstand moderate pollution levels (Augusto & Marcos, 2010).

Coleoptera demonstrate significant diversity, indicating the presence of various microhabitats and substrates they favor. Some Hydrophilidae species possess a broad ecological tolerance for different habitats (Sánchez Fernández et al., 2007; Bennas et al., 2016). Certain species are halophilic and show a particular preference for brackish waters. The presence of Corixidae in the studied areas corroborates their halophilic tendencies, as supported by several studies (Bennas et al., 2016). Some species within this family exhibit a remarkable capacity to colonize and thrive in high salinity environments, including extreme conditions such as salt marshes (Sánchez Fernández et al., 2007).

Oued Z'mor showed superior biodiversity relative to other wadis, but the fauna in Ayata lake, Megarine lake, and Djedi wadi was significantly less diversified. This variance in variety among sites was presumably affected by human-induced disruptions, with certain locations experiencing household pollution. This aligns with the observations of Azrina et al. (2006) and Cereghino et al. (2002), who noted that species richness is affected by human influences on aquatic ecosystems. Aquatic insects, frequently utilized as indicators of environmental conditions in rivers, are especially susceptible to contamination. Consequently, species richness acts as an important indicator of the impacts of human-induced perturbations on river ecosystems (Compin & Cereghino, 2003).

The assessment of the biological quality of the examined hydrosystems, utilizing the IBGN computation, revealed predominantly substandard water quality. The predominant benthic macroinvertebrate families in these wadis exhibit a significant sensitivity to water quality and environmental factors. These families are affiliated with taxa that exhibit a degree of resistance to pollution, including Diptera and Coleoptera (Haouchine, 2011).

## Conclusion

The research results acquired have yielded fresh insights into the dynamics of ecosystems and the macroinvertebrate communities in streams within the dry region of northern Sahara. This research employs macroinvertebrates as ecological indicators and collects environmental data (physical, chemical, and biological) across several geographical scales, thereby advancing the comprehension of the processes that govern stream populations in arid environments and their degradation. Sites with low diversity indices, particularly those demonstrating poor evenness, require vigilant monitoring to identify and mitigate the processes causing changes in these streams and their associated invertebrate ecosystems.

The hydro-systems in this region are persistently impacted by point-source discharges from neighboring communities and agricultural operations, which are markedly human. Continuous monitoring of specific pollution sources would certainly aid in maintaining superior water quality, particularly in areas impacted by harmful human activities. It is essential to broaden this research through more comprehensive investigations, both geographically (across more streams and places) and temporally (longitudinal studies spanning many years and varied seasons). These studies should focus on the characterization of water quality and habitats, together with the composition and dynamics of benthic macroinvertebrate populations, which serve as an ideal biological model for assessing the health of freshwater ecosystems.

It would be imprudent to regard the data as conclusive, as additional research may elucidate how insects react to seasonal and annual variations in environmental structural traits. This research would facilitate predictions about how alterations in habitat conditions may impact insect assemblages.

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