TRANSYLVANIAN REVIEW OF SYSTEMATICAL AND ECOLOGICAL RESEARCH

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Doru Bănăduc, Polina Lemenkova & Karol Plesiński

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IN MEMORIAM

Bjørn Grothaug Andersen
(1924 – 2012)

Bjørn Grothaug Andersen was a Norwegian university teacher of Quaternary geology and glaciology who made opening contributions to glacial geology and the in depth understanding of climate change.

Skiing in the winter and fishing in the summer with his father and brothers in his childhood and teenage periods, adored the mountains in Stavanger region, several times he crossed Trollgaren in Ryfylke, this stunning moraine that is fitting to its name. He questioned how it was shaped, and was said by the farmers of the area that it was truly Trolls that had set up the winding fence of gigantic stones, His interest for this natural phenomenon in addition to many others in turn led to his curiosity and attention for nature in general and Ice Age in special.

In 1951 he married Astrid E. Kruse Andersen which supports his activities all along their common life. Subsequently to a research fellowship at Yale University in 1954-1956, *Andersen* was a teaching quaternary geology at the University of Oslo from 1956 to 1970, then at the University of Bergen for nine years until his retirement. He supervised the geological institutes both in Oslo and Bergen. He was in charge for the geological education of over 30 year groups of students, and he unrelenting participated to the academic world activities until autumn 2011, when he was hit by a cancer and he was in poor health.

All along his activity, his students and colleagues benefited from his expertise and international contacts. He conducted field trips to the Antarctic, South America, New Zeeland, Greenland, etc. *Andersen* kept in contact with some of his students until his death.

Andersen's first scientific journey to the South Pole came after a period of small Norwegian interest in the Antarctic after the great achievements of Roald Amundsen in 1911-1912. *Andersen* was the next Norwegian to visit the Pole after the Amundsen successful mission. An America expedition which reached the Pole a week before *Andersen* revered his realisations by naming a mountain escarpment (Andersen Escarpment) after him.

He accompanied along his activity a party of scientists doing research in Norway, Chille, New Zeeland, Greenland, etc.

Among such trips, in 2005 *Andersen* with a group of scientists went on a research voiage to Greenland to measure the ice coverage in connection to climatic change.

All his research led to a succession of works, among them papers in the respected international scientific journals *Nature* and *Science*. In addition, to two significant books on glacial geology, one about the Ice Age in Norway (Ice age Norway: landscapes formed by ice age glaciers) and an international textbook on the World Ice Age (The Ice Age World: an introduction to Quaternary history and research with emphasis on North America and Northern Europe during the last 2.5 million years) were published. Among numerous valuable scientific papers, Amundsen's first paper is one of the most basic papers in Norwegian glacial geology, even thought it was published before C-14 dating was available.

Bjørn Grothaug Andersen was a dedicated naturalist all his adult life, letting an important scientific legacy in his field of activity.

The Editors

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Preface

In a global environment in which the climate changes are observed from few decades no more only through scientific studies but also through day by day life experiences of average people which feel and understand allready the presence of the medium and long-term significant change in the "average weather" all over the world, the most comon key words which reflect the general concern are: heating, desertification, rationalisation and surviwing.

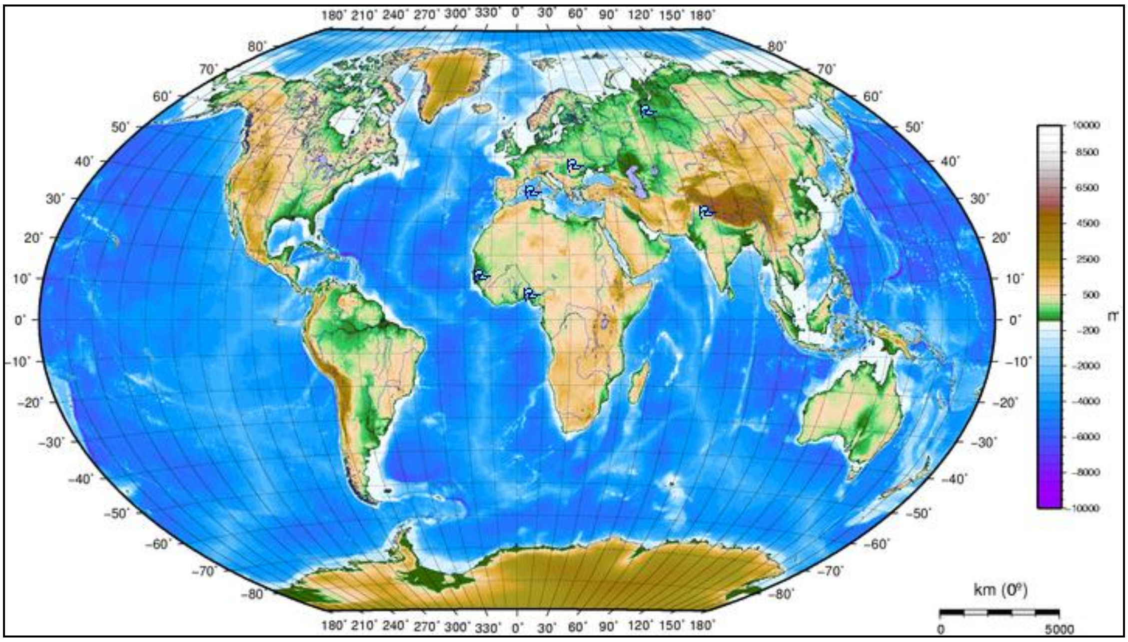
The causes, effects, trends and possibilities of human society to positively intervene to slow down this process or to adapt to it involve a huge variety of aproacess and efforts.

With the fact in mind that these aproaces and efforts shuld be based on genuine scientific understanding, the editors of the *Transylvanian Review of Systematical and Ecological Research* series launch three annual volumes dedicated to the wetlands, volumes resulted mainly as a results of the *Aquatic Biodiversity International Conference*, Sibiu/Romania, 2007-2024.

The therm wetland is used here in the acceptance of the Convention on Wetlands, signed in Ramsar, in 1971, for the conservation and wise use of wetlands and their resources. **Marine/Coastal Wetlands** – Permanent shallow marine waters in most cases less than six metres deep at low tide, includes sea bays and straits; Marine subtidal aquatic beds, includes kelp beds, sea-grass beds, tropical marine meadows; Coral reefs; Rocky marine shores, includes rocky offshore islands, sea cliffs; Sand, shingle or pebble shores, includes sand bars, spits and sandy islets, includes dune systems and humid dune slacks; Estuarine waters, permanent water of estuaries and estuarine systems of deltas; Intertidal mud, sand or salt flats; Intertidal marshes, includes salt marshes, salt meadows, saltings, raised salt marshes, includes tidal brackish and freshwater marshes; Intertidal forested wetlands, includes mangrove swamps, nipah swamps and tidal freshwater swamp forests; Coastal brackish/saline lagoons, brackish to saline lagoons with at least one relatively narrow connection to the sea; Coastal freshwater lagoons, includes freshwater delta lagoons; Karst and other subterranean hydrological systems, marine/coastal. **Inland Wetlands** – Permanent inland deltas; Permanent rivers/streams/creeks, includes waterfalls; Seasonal/intermittent/irregular rivers/streams/creeks; Permanent freshwater lakes (over eight ha), includes large oxbow lakes; Seasonal/intermittent freshwater lakes (over eight ha), includes floodplain lakes; Permanent saline/brackish/alkaline lakes; Seasonal/intermittent saline/brackish/alkaline lakes and flats; Permanent saline/brackish/alkaline marshes/pools; Seasonal/intermittent saline/brackish/alkaline marshes/pools; Permanent freshwater marshes/pools, ponds (below eight ha), marshes and swamps on inorganic soils, with emergent vegetation water-logged for at least most of the growing season; Seasonal/intermittent freshwater marshes/pools on inorganic soils, includes sloughs, potholes, seasonally flooded meadows, sedge marshes; Non-forested peatlands, includes shrub or open bogs, swamps, fens; Alpine wetlands, includes alpine meadows, temporary waters from snowmelt; Tundra wetlands, includes tundra pools, temporary waters from snowmelt; Shrub-dominated wetlands, shrub swamps, shrub-dominated freshwater marshes, shrub carr, alder thicket on inorganic soils; Freshwater, tree-dominated wetlands; includes freshwater swamp forests, seasonally flooded forests, wooded swamps on inorganic soils; Forested peatlands; peatswamp forests; Freshwater springs, oases; Geothermal wetlands; Karst and other subterranean hydrological systems, inland. **Human-made wetlands –** Aquaculture (e. g., fish/shrimp) ponds; Ponds; includes farm ponds, stock ponds, small tanks; (generally below eight ha); Irrigated land, includes irrigation channels and rice fields; Seasonally flooded agricultural land (including intensively managed or grazed wet meadow or pasture); Salt exploitation sites, salt pans, salines, etc.; Water storage areas, reservoirs/barrages/dams/impoundments (generally over eight ha); Excavations; gravel/brick/clay pits; borrow pits, mining pools; Wastewater treatment areas, sewage farms, settling ponds, oxidation basins, etc.; Canals and drainage channels, ditches; Karst and other subterranean hydrological systems, human-made.

The editors of the *Transylvanian Review of Systematical and Ecological Research* started and continue the annual sub-series (*Wetlands Diversity*) as an international scientific debate platform for the wetlands conservation, and not to take in the last moment, some last heavenly "images" of a perishing world …

This volume included variated original researches from diverse wetlands around the world.



The subject areas (⚑) for the published studies in this volume.

No doubt that this new data will develop knowledge and understanding of the ecological status of the wetlands and will continue to evolve.

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The Editors

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CARBON SEQUESTRATION CAPACITY OF THE LAGOS LAGOON: EXAMINING THE POTENTIALS OF A TYPICAL NIGERIAN COASTAL ECOSYSTEM FOR CLIMATE CHANGE MITIGATION

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KEYWORDS: climate change, carbon sequestration, coastal ecosystems.

ABSTRACT

Carbon sequestration capacity of the Lagos Lagoon was studied through a six-month analysis of carbon surrogates. The findings revealed that water samples from inorganic carbon surrogates yeilded higher values than those of organic carbon. Sediment samples recorded higher values of DOC, DIC, TOM, TIM, and TOC. Correlation studies indicate that DOC, DIC, and TOM were the principal determinants of the trends observed in most parameters. A total of 1.5 x 5.3 x 10^{-11} t CO_2 eq ha^{-1}, was sequestered in the surface water, while in sediment, the lagoon demonstrated a sequestration potential of 2.13 x 10^{-6} t CO_2 eq ha^{-1}. Biomass of benthic macrofauna populations was a major contributor to the carbon stock and CO_2 sequestered. The low value of carbon sequestered in the lagoon can be attributed to the wide-scale human disturbances taking place in the lagoon.

RÉSUMÉ: Capacité de séquestration du carbone dans la lagune de Lagos: examen du potentiel d'un écosystème côtier typique du Nigéria pour l'atténuation du changement climatique.

La capacité de séquestration du carbone de la lagune de Lagos a été étudiée par analyse de substituts de carbone pendant six mois. Les valeurs des paramètres étudiés ont révélé que les échantillons d'eau enregistraient des valeurs plus élevées de substituts de carbone inorganique que celles de carbone organique. Les sédiments ont enregistré des valeurs plus élevées de DOC, DIC, TOM, TIM et TOC. Des études de corrélation indiquent que le COD, le DIC et le TOM étaient les principaux déterminants des tendances enregistrées pour la plupart des paramètres. Au total, 1,5 x 5,3 x 10-11 t CO_2 eq ha-1 ont été séquestrées dans les eaux de surface, tandis que dans les sédiments, le la lagune a démontré un potentiel de séquestration de 2,13 x 10-6 t CO_2 eq ha-I. La biomasse des populations de macrofaune benthique était un contributeur majeur au stock de carbone et au CO_2 séquestré. La faible valeur du carbone séquestré dans le lagon peut être attribuée aux perturbations humaines à grande échelle qui ont lieu dans le lagon.

REZUMAT: Capacitatea de sechestrare a carbonului a lagunei Lagos: examinarea potențialului unui ecosistem tipic de coastă Nigeriană pentru atenuarea schimbărilor climatice.

Capacitatea de captare a carbonului a lagunei Lagos a fost investigată prin analiza surogatelor de carbon timp de șase luni. Valorile parametrilor investigați au evidențiat că, probele de apă au înregistrat valori mai mari ale surogatelor carbonului anorganic decât cele ale carbonului organic. Sedimentul a înregistrat valori mai mari ale DOC, DIC, TOM, TIM și TOC. Studiile de corelare indică faptul că DOC, DIC și TOM au fost principalii determinanți ai tendințelor înregistrate pentru majoritatea parametrilor. Un total de 1,5 x 5,3 x 10-11 t CO_2 eq ha-1, a fost sechestrat în apa de suprafață, în timp ce în sediment, laguna a demonstrat un potențial de sechestrare de 2,13 x 10-6 t CO_2 eq ha-I. Biomasa populațiilor de macrofaună bentonică a contribuit major la stocul de carbon și CO_2 sechestrat. Valoarea scăzută a carbonului captat în lagună poate fi atribuită perturbărilor umane la scară largă din lagună.

INTRODUCTION

The Paris Agreement under the UNFCCC requires signatories to pursue ambitious measures to reduce the rising global temperature to 1.5°C. There is an urgent need for rapid decarbonization of the economy. Although this process alone will not be sufficient to achieve the desired result, IPCC scenarios for limiting global temperature rise to 1.5°C also require the removal of CO_2 from the atmosphere (IPCC, 2013). One of the main approaches to achieving this is through nature-based solutions (NbS) that conserve and expand natural carbon sinks, providing climate change mitigation benefits along with co-benefits to society and biodiversity (IUCN, 2020). Climate change is a major threat to natural ecosystems and a substantial barrier to sustainable development (IPCC, 2014). The topic of climate change has attracted significant research interest in the search for ways to slow down the process and reduce its impact.

Policies towards climate mitigation aim to store carbon in ecosystems, which can result in lower carbon dioxide levels in atmosphere. Intact, well-functioning ecosystems can store and conserve large amounts of carbon, and restoration of degraded aquatic ecosystems could contribute significantly to reducing further carbon dioxide emissions from these systems or even removing them from the atmosphere and sequesting the carbon in biomass and sediment (IPCC, 2014). Because of this, in both terrestrial and aquatic ecosystems, reforestation and restoration are recommended as methods of reducing CO_2 in the atmosphere.

Relying on ecosystem services to address climate change is the core principle behind the adoption of NbS for climate change mitigation. Carbon dioxide stored in aquatic environments can take a long time before it is released to the surface water from the sediment through geologic processes. Aquatic ecosystems, especially the oceans, are the largest long-term stock of carbon in the biosphere, capable of storing and cycling approximately 93% of the Earth's estimated 40 Tt of CO_2 (Moraes, 2019). It has been reported that a large percentage of carbon in the oceans occurs in the form of inorganic carbon, mainly as bicarbonate, carbonate, dissolved carbon dioxide, and carbonic acid (Hansell, 2013), and that carbon is stored in the ocean in three forms (Dickson et al., 2007): dissolved inorganic carbon (CO_2, HCO_3^-, CO_3^{2-}), dissolved organic carbon (both small and large organic molecules), and particulate organic carbon (live organisms or fragments of dead plants and animals).

Planetary carbon cycling involves the transfer and exchange of carbon among its four main reservoirs: the atmosphere, the terrestrial biosphere, the ocean, and the sediment (Tank et al., 2012). Aquatic ecosystems can have a major impact on the reduction of atmospheric CO_2 concentrations, thereby reducing climate change, through CO_2 sequestration from the atmosphere and the uptake of CO_2. Climate change mitigation can be more cost-effective if it involves an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize the energy supply, reduce net emissions, and enhance the storage of carbon stocks (IPCC, 2014).

Nigeria is blessed with enormous aquatic resources including a large network of rivers, coastal lagoons, adjacent ocean mass, creeks, etc. However, the potential of these ecosystems to sequester or store carbon has not been appraised and fully integrated into the nation's Nationally Determined Contribution (NDC) as part of its nature-based solutions to climate mitigation. This is primarily due to scarce or nonexistent data on the potential of aquatic systems in climate mitigation in Nigeria. In this study, therefore, we have investigated the capacity of one of the largest lagoons in Nigeria, the Lagos Lagoon, to sequester carbon with the aim of determining its potential for climate mitigation. This study is likely the first to provide such information. This will help policymakers and other stakeholders by supplying data to implement actions toward national and regional strategies on carbon storage and the adoption of blue carbon in climate mitigation endeavors.

MATERIAL AND METHODS

Background

The Lagos Lagoon located in the heart of the commercial nerve center of the city of Lagos is a major sink for over 70% of the surface runoffs, drainage channels, and important rivers flowing from Nigeria hinterland to the Atlantic Ocean. The surrounding densely populated and industrialized areas often result in the introduction of large quantities of organic waste into the lagoon. The city of Lagos has been recognized as the most populous in Nigeria and the fifth most populous city in the world. The city hosts about 75% of the industries in Nigeria, and owing to the large population, coupled with the high number of industries, enormous quantities of waste are discharged into the lagoon. In addition, active dumping of solid waste into the lagoon continues unabated. The lagoon serves as a major waste sink. The lagoon geology is dominated by a continuous repetition of clay and sand (Olatunji and Abimbola, 2010). The lagoon is bounded in the north by a broad land area, housing a large human population and industrial centers, and to the south by highbrow business and residential areas. The lagoon is lined with several shanty settlements along its banks. The depth of the lagoon ranges mostly between 2-3 m, with some areas reaching 10-15 m deep. The lagoon maintains a fairly constant volume of water throughout the year. During the wet season, the lagoon is fed by numerous rivers and creeks, while in the dry periods, the loss of water due to evaporation and the reduced input from rivers and creeks are compensated by the underground seepage through the active sandy barrier formation and inflow of tidal waters from the sea to the Lagos Harbor and other lagoon outlets originating in southwest Nigeria.

Field studies

In-situ measurements were taken for three parameters: air temperature, water temperature, and surface water pH. Air temperature was measured using a mercury-in-glace thermometer, while water temperature and pH of surface water were measured with a hand-held Horiba U-10 water quality checker.

Collection of samples

Samples of water, sediment, and benthic macrofauna were collected from five stations spanning about one-third of the entire length of the lagoon, for six consecutive months from June to November 2023, representing the rainy season.

The water samples were collected in pre-washed one-litre plastic bottles which were properly corked, labeled, and kept in a cooler for transport to the laboratory. Sediment and macrofauna samples were collected with a benthic van Veen Grab of 1 x 1 sqm. Three successfully retrieved grab samples were taken from each sampling station, on each sampling day. All samples were immediately homogenized after collection. A portion of the homogenized sample was taken with a plastic spatula, wrapped with aluminum foil, and properly labeled. The remaining sediment was washed through a 0.5 mm sieve to extract the macroinvertebrates. The materials retained in the sieve were placed in a wide-mouth plastic bottle with a screw cap and properly labeled. All collected samples were kept in a well-sealed cooler and taken to the laboratory for analyses of carbon and organic matter.

Laboratory studies

The laboratory studies involved the determination of carbon content and organic matter of samples, including: dissolved organic carbon (DOC) in water and sediment, dissolved inorganic carbon (DIC) in water and sediment, total organic carbon (TOC) in water and sediment, total inorganic carbon (TIC) in water and sediment, total organic matter (TOM) in water and sediment, and biomass of macrofauna.

Dissolved organic carbon in sediment and water was determined by the Dittmar et al. method (2008). 10.0-g sediment samples were sieved with a 2 mm sieve, mixed with 50 mL of 2 M KCl in a polyethylene bottle (100 mL), then shaken for 1 h in an oscillator. 100 Ml of water was filtered on a Whatmann filter paper. After shaking, centrifugation, and filtration, of both the sediment and water samples, the DOC of the samples were determined by a total-C analyzer (TOC-L CPN, Shimadzu, Japan) using a standard curve method (Yang et al., 2021).

Dissolved inorganic carbon determination in water and sediment was accomplished by converting bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}) to undissociated CO_2, which is then extracted as a gas for quantification. Five grams of sediment was extracted with 100 mLs of CO_2-free water and filtered. Similarly, 100 mL of water sample was filtered to remove particulates and stored in an airtight borosilicate bottle. The water and sediment extracts were acidified by adding a strong acid (e.g., phosphoric acid) to convert HCO_3^- and CO_3^{2-} to CO_2. The evolved CO_2 gas was extracted using a dynamic headspace system that trapped the CO_2 gas for subsequent analysis. An Apollo SciTech DICOMAT dissolved inorganic Carbon Analyzer (DIC Analyzer), specifically designed for DIC measurement utilizing infrared detection of CO_2, was used to measure total DIC directly.

The organic compounds in the samples were converted to CO_2 by oxidation. The CO_2 produced was analyzed using high temperature combustion. The samples were combusted at 1,200°C in an oxygen-rich atmosphere and the resulting CO_2 was measured using a Shimadzu TOC-V non-dispersive infrared (NDIR) absorption spectrometer (Yang et al., 2021).

Organic forms of carbon are oxidized in the presence of excess dichromate. Total organic carbon was determined using the back titration method (Walkley and Black, 1934). 10 g of dried sediment was weighed and transferred to a 500 mL Erlenmeyer flask and 10 mL of 1 molar solution of potassium dichromate was added. Then, 20 mL of concentrated sulphuric acid was added. The flask was agitated by rotation for one minute to homogenize at a reaction of temperature 120°C. The flask was placed on an insulating plate and the oxidation was allowed to continue for another 30 minutes. Two hundred (200) mL of distilled water was added, followed by 10 mL of phosphoric acid. Five g of sodium fluoride was also added. The flask and its contents were homogenized. Three drops of diphenylamine were added as a titration indicator. The excess dichromate was titrated with 0.5 mol ferrous iron solution. The titration was continued until the color changed from purplish blue to luminous greenish blue. Determination of the endpoint was facilitated by the addition of 1-2 drops of indicator as soon as the color began to change. Total organic carbon of dried sediment was 100 x 3.9 (10-V)/ P, where P is the sample mass in g and V is the volume (mL) of Fe^{2+} solution at a concentration of 0.5 mol per liter. Total organic matter (g kg^{-1}) = Total organic carbon x (1.1-1.7). For total organic matter in water, this method was repeated with 100 mL of water sample.

Five grams of dried sediment and 100 mL of water were used for TOM determination. The dried homogenized sediment sample was combusted at 1,350°C in an oxygenated atmosphere. Carbon in the sample oxidized to form CO_2 gas. The CO_2 gas flowed through a non-dispersive infrared (NDIR) detection cell. A LECO CR-412 Carbon Analyzer, designed for TIC measurement., provided weight-corrected results as percentage carbon. The process was repeated for the 100 mL water sample. (Bernard et al., 1995)

Biomass was determined by wet method, weighing all specimens of *Pachmylenia aurita* in macrofauna samples (Holme and Mclntyre, 1971). These specimens were dried for five minutes after puncturing the shells with a needle. The mantle cavity water was absorbed using filter paper. The specimens were then weighed with a balance and values were recorded as the total weight (TWT) approximated to the nearest gram (g). Tissue weight (TSW) was obtained after weighing deshelled specimens and values were recorded in grams.

RESULTS AND DISCUSSION

Spatial and temporal patterns in parameters investigated

Table 1 shows the summary of values recorded for the parameters investigated, and spatiotemporal variations in values observed are depicted (Figs. 1-10). While seven parameters (DOC, DIC, TOM, TIM, TIC, temperature, and pH) were studied for water samples, five (DOC, DIC, TOM, TIM, and TIC) and two (TWA and TWT) parameters were investigated for sediment and macrofauna respectively. Values of DOC in water samples varied from 0.1 to 1.6 $mgCL^{-1}$. Relatively higher values of DOC were recorded in station 4 where recorded ranged from of 0.7 to 1.6 mgCL-1 was observed. Mean values for study stations fluctuated from 0.3 to 1.0 $mgCL^{-1}$ while monthly mean values varied from 0.4 to 0.8 $mgCL^{-1}$. Values of DIC in water were significantly higher than those of DOC. The range of values observed for DIC were from 208 to 9,600 $mgCL^{-1}$. Spatially, mean values fluctuated from 566 to 5,023 $mgCL^{-1}$, while temporal changes in mean values fell from 227.2 to 4,272 $mgCL^{-1}$.

Values of TOM did not show notable variation during the study. All values encountered were between 2.0 to 7.2 $mgCL^{-1}$. Among the study locations, mean values varied from 4 to 11 $mgCL^{-1}$, while mean values recorded for sampling months ranged from five to eight $mgCL^{-1}$. The concentrations of TOC varied greatly among stations and sampling months. Values recorded were ffrom 1.6 to 5.0 $mgCL^{-1}$ which is closely related to TOM concentrations. While temporal ranges in mean concentration fluctuated from 2.1 to 4.0 $mgCL^{-1}$, ranges in mean spatial concentrations varied from 1.4 to 4.2 $mgCL^{-1}$. Values of TIM were similar in range (280 to 10,200 $mgCL^{-1}$) to those recorded for DIC. At the study locations mean concentration of TIM varied from 727 to 5,267 $mgCL^{-1}$, whereas in sampling locations, the mean concentration ranged from 308.4 to 4,537 $mgCL^{-1}$. The temperature of surface water did not show remarkable variations during the study period. Values recorded for pH also demonstrated the same trend. While values encountered for temperature were ranged from 25.3 to 29.99°C, pH fluctuated from 4.6 to 7.7.

Sediment samples recorded higher values of DOC, DIC, TOM, TIM, and TOC. Dissolved organic carbon varied between 2.0 and 14.0 $mgCkg^{-1}$. On the spatial scale, mean values ranged from 2.0 to 12.0 $mgCkg^{-1}$, while a range from 6.0 to 7.0 $mgCkg^{-1}$ was observed at the temporal scale. Similar to the pattern recorded for water samples, DIC values for sediment were higher than those of DOC. Values fluctuated from 7.5 to 32.6 $mgCkg^{-1}$. Mean values recorded in the study location ranged from 10.0 to 44.0 $mgCkg^{-1}$, while monthly mean values obtained during the six-month sampling period were from 24.0 to 30.0 $mgCkg^{-1}$. Concentrations of TOC were similar in range (3.0 to 13.6 $mgCkg^{-1}$) to those observed for DOC. Spatially, mean concentrations varied from 4.0 to 11.4 $mgCkg^{-1}$ and temporarily fluctuated from 6.7 to 8.2 $mgCkg^{-1}$. Concentrations of TOM and TIM in the study stretch varied remarkably both at spatial and temporal scales. Overall values of TIM were higher than TOM in all the sampling stations during the study period. Whereas a range from 5.0 to 20.7 $mgCkg^{-1}$ was observed for TOM, TIM concentrations fluctuated from 14.2 to 80.0 $mgCkg^{-1}$.

Table 1: Summary of values of parameters investigated.

Parameter	Sampling location									
	1		2		3		4		5	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Water										
DOC (mgCL[1])	0.1 – 0.5	0.3	0.2 – 0.6	0.4	0.2 – 0.8	0.4	0.7 – 1.6	1.0	0.3 – 0.5	0.4
DIC ($mgCL^{-1}$)	218 – 960	566	208 – 4800	1806	280 – 5200	2198	210 – 9600	5023	220 – 1000	694
TOM ($mgCL^{-1}$)	2 – 5	4	4 – 6	5	3 – 6	5	6 – 17	11	3.1 – 7.2	5
TIM ($mgCL^{-1}$)	280 – 1560	727	320 – 5200	2402	300 – 5425	2436	280 – 10200	5267	298 – 1200	835
TOC ($mgCL^{-1}$)	2.0 – 4.0	3.0	4.0 – 5.0	4.0	2.8 – 4.2	3.5	1.6 – 4.9	3.0	0.56 – 2.6	1.4
Tempt °C	26.1 – 29.99	28.4	26.2 – 29.51	28.4	25.4 – 29.68	28.2	25.3 – 29. 9	27.7	25.9 – 29.9	28.3
pH	6.0 – 7.0	7.0	5.8 – 6.8	6.3	5.3 – 6.7	6.2	4.6 – 7.4	6.2	5.5 – 7.7	6.7
Sediment										
DOC ($mgCkg^{-1}$)	2 – 3	2	5.2 – 6.6	6	5.3 – 7.6	6	9.8 – 13.6	12	4.6 – 6.4	6
DIC ($mgCkg^{-1}$)	40 – 50	44	25.6 – 30.6	28.6	27.0 – 32.6	29.7	7.5 – 15.6	10.4	16.4 – 23.7	20.4
TOC ($mgCkg^{-1}$)	3 – 5	4	6.0 – 9.5	7.8	6.1 – 9.3	8.2	8.6 – 13.5	11.4	5.3 – 8.9	6.8
TOM ($mgCkg^{-1}$)	5 – 10	6	11.6 – 13.5	12.5	11.6 – 15.2	13.7	17.2 – 20.7	19	7.2 – 12.5	10
TIM ($mgCkg^{-1}$)	68.5 – 80.0	73	46.2 – 52.6	49.3	50.2 – 56.6	53.3	14.2 – 23.6	17.6	30.6 – 44.6	38.4
Macrofauna										
Total Weight (g)	21 – 750	190	35.1 – 56.0	49.0	12.0 – 536.0	208.0	10.3 – 36.0	27	28.0 – 200	67
Tissue weight (g)	1.2 – 16.0	5.1	1.0 – 12.0	4.1	0.5 – 13.0	4.4	0.5 – 10.0	2.6	1.1 – 17.0	4.7

Total and tissue weights of collected macrofauna specimens varied significantly. The total weight (TWT) values ranges from 10.3 to 750.0 g, while tissue weight (TSW) values ranged between 0.5 and 7.0 g.

A critical evaluation of the patterns demonstrated in values of parameters investigated in this study revealed two outstanding features. Firstly, water samples recorded higher values of parameters related to inorganic carbon (DIC and TIM) than organic carbon (DOC, TOM, and TOC). This trend is expected as most of the carbon in the aquatic systems exist as DIC, in the forms of bicarbonate, carbonate, dissolved CO_2, and carbonic acid (Hansell et al., 2009). Dissolved inorganic carbon in aquatic environments originates from different sources including sediment carbonate dissolution, organic matter decay, and carbonate rock disintegration with source contribution depending on flora composition, climatic conditions, and lithology (Lloret et al., 2011). A similar relationship was observed in the waters of Port Blair, Andaman Islands, and India, consistent with the findings in this study (Mohan et al., 2016). Carbon in organic matter such as DOC, is subject to microbial mineralization and most of the organic carbon will be converted back to DIC within a few decades (Soria-Reinoso et al., 2022). It is estimated that about 1% of TOC from the surface is exported to deeper sediment where it can be buried for thousands of years. The variation of DOC and DIC in aquatic systems is usually dependent on the subsurface dissolved carbon transport dynamics (Jantze et al., 2015). The rate at which water percolates through the sediment significantly impacts the degree of mineralization from organic to inorganic carbon (Ågren et al., 2007).

Carbon (iv) oxide is the raw material with which organic materials are synthesized. The catalysis of these organic molecules results in the release of CO_2 and the formation of inorganic carbon, meaning that, the breaking down of organic materials results in an increased release of inorganic carbon. Thus, the inverse relationship recorded between DIC and DOC in this study is valid and represents the opinions of many researchers in this field. Values (0.1-01.6 $mgCL^{-1}$) of DOC recorded in water compare favorably with the data (2.02± 0.91 mgCL-1) reported for Godavari River (Bouillon et al., 2002), but were lower than values (2.4-16.1 $mgCL^{-1}$) recorded for major world rivers (Spitzy and Leenheer, 1991).

Secondly, the values of the parameters studied were generally higher in sediment than in surface water samples, confirming the postulation that sediment serves as a sink to materials entering the aquatic ecosystem. This observation is consistent with the results of similar studies (Niemirycz et al., 2006).

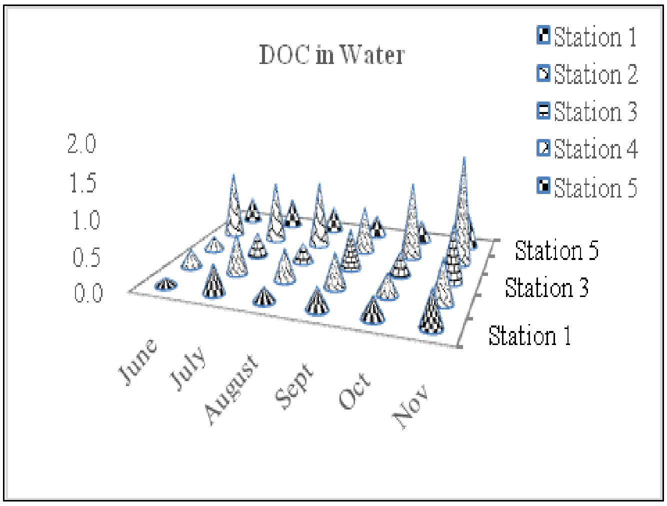

Figure1: Spatiotemporal variations in surface water DOC.

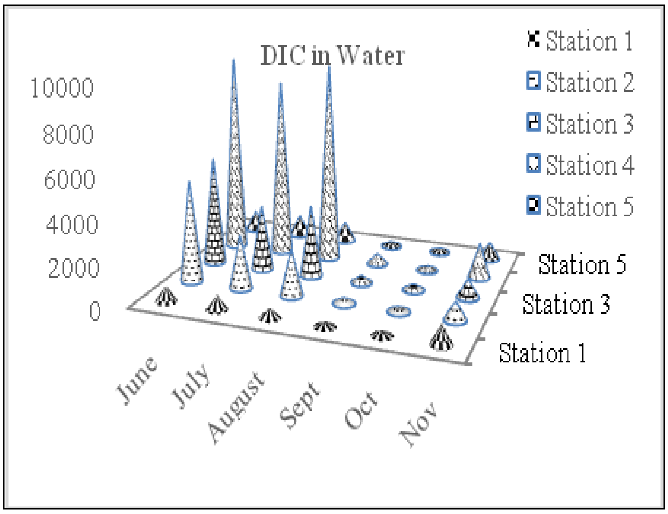

Figure 2: Spatiotemporal variations in surface water DIC.

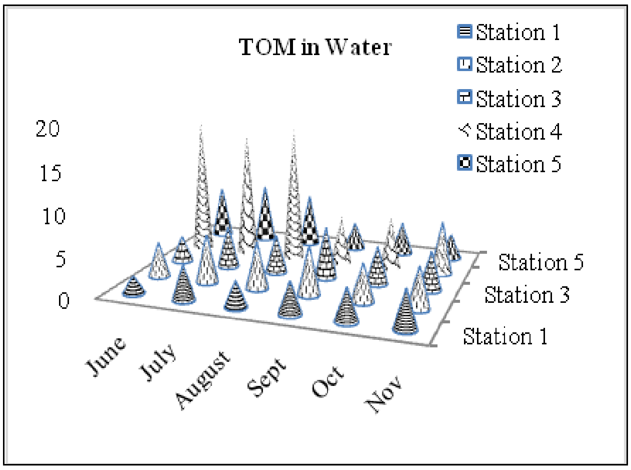

Figure 3: Spatiotemporal variations in surface water TOM.

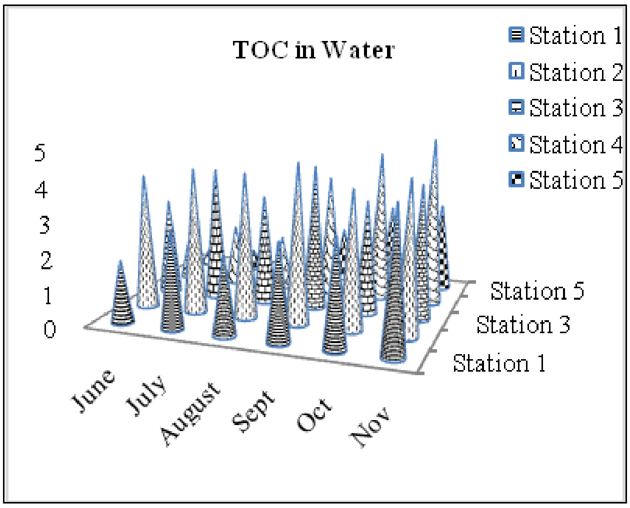

Figure 4: Spatiotemporal variations in surface water TOC.

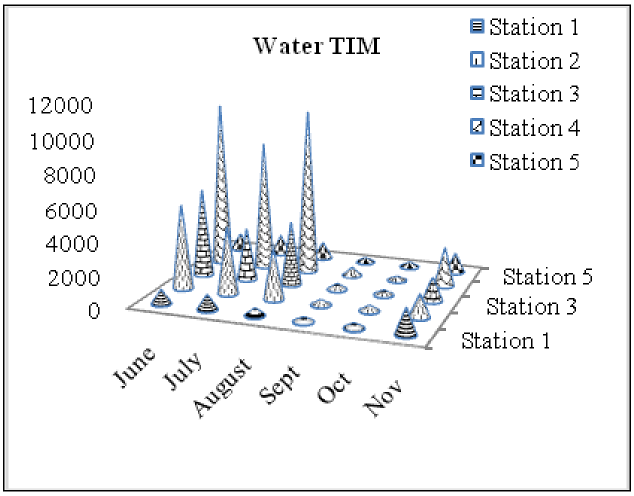

Figure 5: Spatiotemporal variations in surface water TIM.

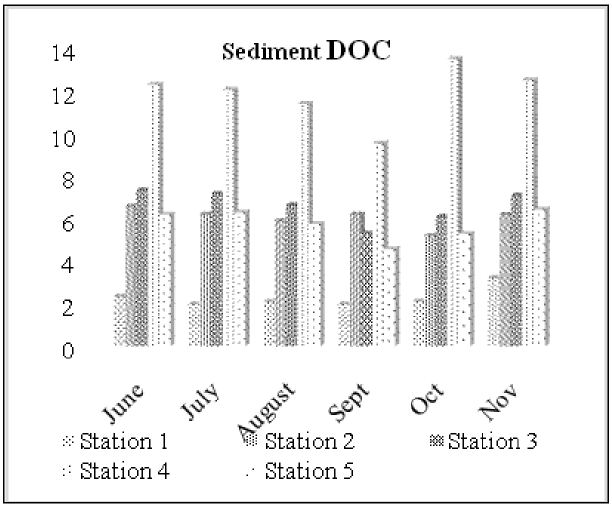

Figure 6: Spatiotemporal variations in sediment DOC.

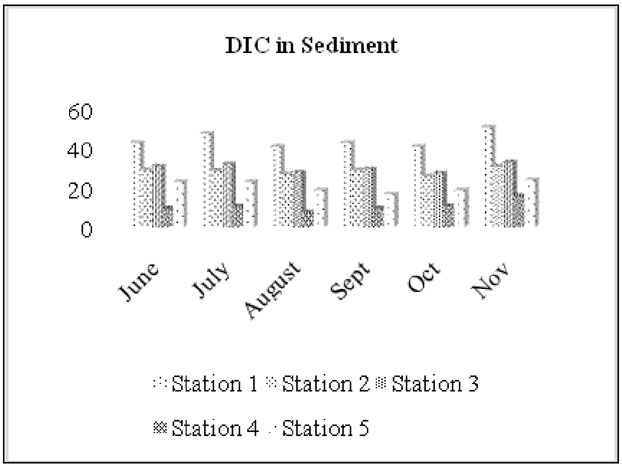

Figure 7: Spatiotemporal variations in sediment DIC.

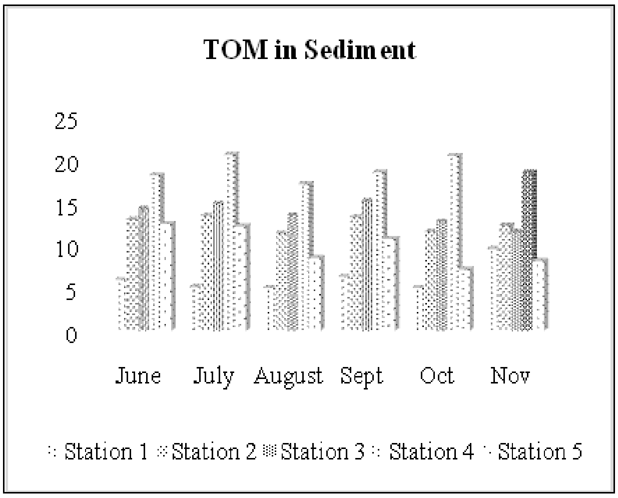

Figure 8: Spatiotemporal variations in sediment TOM.

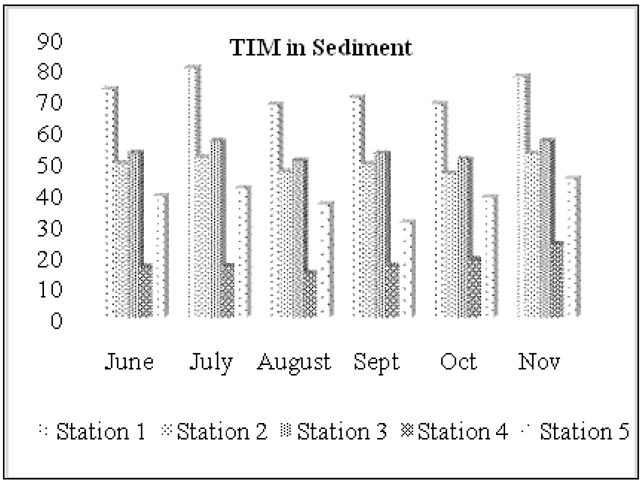

Figure 9: Spatiotemporal variations in sediment TIM.

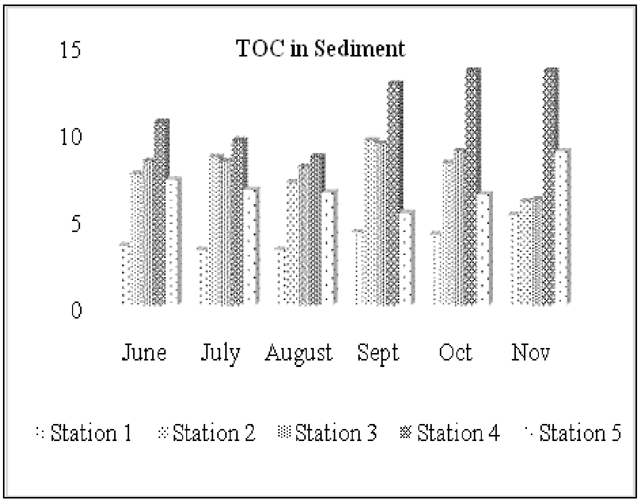

Figure 10: Spatiotemporal variations in sediment TOC.

Correlation analysis and the relationship between parameters

Tables 2 and 3 depict relationships among the investigated parameters. There were positive and significant relationships between most of the parameters. Correlation studies showed that DOC, DIC, and TOM were the principal determinants of the trends observed in most parameters. For water samples, DOC was positively and significantly correlated with DIC (p = 0.05; r = 0.96), TOM (p = 0.05; r = 099), and TIM (P = 0.05; r= 0.95). Dissolved inorganic carbon also exhibited a positive and significant correlation with TOC (P = 0.99; r = 0.99), TOM (p = 005; r = 0.94), and TIM (p = 0.05; r = 0.99). Additionally, a positive and significant relationship was found between TIM and TOC (p = 0.05; r = 0.73) and TOM (P = 0.05; 0.92). An outstanding feature of the results is the significant negative relationship between pH and all the surrogates of carbon. This observation aligns with the report of Wenxiang et al. (2019) that pH significantly influences TOC contents by controlling bioavailability of minerals, organic matter turnover and other sedimentary processes (Wenxiang et al., 2019). Furthermore, the solubility of organic matter is dictated by pH.

Table 2: Correlation coefficient for the parameters investigated in water samples.

Water	DOC ($MGCL^1$)	DIC ($MGCL^1$)	TOC ($MGCL^1$)	TOM ($MGCL^1$)	TIM ($MGCL^1$)	PH
DOC ($mgCL^1$)	1	–	–	–	–	–
DIC ($mgCL^1$)	0.96	1	–	–	–	–
TOC ($mgCL^1$)	0.08	0.99	1	–	–	–
TOM ($mgCL^1$)	0.99	0.94	0.003	1	–	–
TIM ($mgCL^1$)	0.95	0.99	0.73	0.92	1	–
pH	–0.6	–0.79	–0.66	–0.57	–0.83	1

In sediment samples, a slightly different trend was observed in the relationship and correlation analysis. While a significantly positive relationship was established between DOC and DIC (p = 0.05; r = 0.91), TOC (p = 0.05; r = 0.98), TOM (p = 0.05; r = 0.97), TIM (p = 0.05; r = 0.93), there was a significantly negative relationship between DIC and TOC (p = 0.05; r = –0.89) and TOM (p = 0.05; r = –0.83). Biomass, expressed in the forms of TWT and TSW of the benthic macrofauna, exhibited different relationships with non-animal parameters. Total weight demonstrated a significant negative relationship with parameters of organic carbon (DOC, TOC, TOM), and inorganic carbon (DIC and TIM). A similar trend was demonstrated between TSW and parameters of sediment.

Values recorded for TWT and TSW showed a significant positive correlation (p = 0.05; r = 0.64) in the area during the period of the study, indicating the importance of shell size in determining the size of tissue accommodated.

Table 3: Correlation coefficient for the parameters investigated in sediment sample.

Sediment	DOC ($mgCkg^{-1}$)	DIC ($mgCkg^{-1}$)	TOC ($mgCkg^{-1}$)	TOM ($mgCkg^{-1}$)	TIM ($mgCkg^{-1}$)	TWT (g)	TSW (g)
DOC ($mgCkg^{-1}$)	1	–	–	–	–	–	–
DIC ($mgCkg^{-1}$)	0.91	1	–	–	–	–	–
TOC ($mgCkg^{-1}$)	0.98	–0.89	1	–	–	–	–
TOM ($mgCkg^{-1}$)	0.97	–0.83	0.99	1	–	–	–
TIM ($mgCkg^{-1}$)	0.93	0.99	–0.9	0.84	1	–	–
TWT (g)	–0.61	0.77	–0.59	–0.51	0.78	1	–

Carbon sequestration and storage

From the parameters investigated, a total of 1.5 x 10^{-11} t C ha^{-1}, approximately 5.3 x 10^{-11} t CO_2 eq ha^{-1}, was sequestered and stored in the surface water of the lagoon during the study period. The contributions of the different parameters were as follows: DIC was 6.8 x 10^{-12} t C ha^{-1}, approximately 2.5 x 10^{-11} t CO_2 eq ha^{-1}; DOC was 1.7 X 10^{-15} t C ha^{-1}, approximately 6.3 x 10^{-15} t CO_2 eq ha^{-1} and TIM was 7.7 x 10^{-12} t C ha^{-1}, approximately 2.8 x 10^{-11} t CO_2 eq ha^{-1}. Others were TOM, which recorded 1.98 x 10^{-14} t C ha^{-1}, approximately 7.3 x 10^{-14} t CO_2 eq $ha^{-1}$and TOC which contributed a value of 9.8 x 10^{-15} t C ha^{-1}, approximately 6 x 10-^{14} t CO_2 eq ha^{-1}. Evaluation of the results indicates that, TIM (53%) and DIC (47%) were the major contributors to the carbon stock and sequestered CO_2 in surface water. Contributions by other parameters were negligible (Fig. 11).

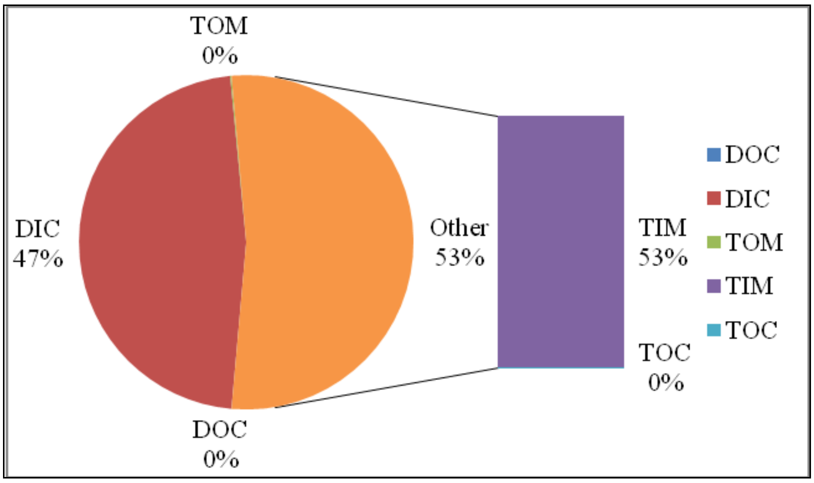

Figure 11: Percentage contribution of parameters of CO_2 sequestration and storage in surface water.

In sediment, the lagoon demonstrated a sequestration and storage potential of 5.8 x 10^{-7}t C ha^{-1}, approximately 2.13 x 10^{-6} t CO_2 eq ha^{-1}. Analysis shows that the biomass of the benthic species *Pachmylenia aurita* contributed the highest percentage of carbon stock and the sequestered 2.13 x 10^{-6} t CO_2 eq ha^{-l} recorded in sediment (Fig. 12). Specificlly, TWT contributed with 76% of the carbon stock and CO_2 sequestered carbon, and TWS contributed 24%. The contributions of DIC, DOC, TOM, TIM, and TOC were highly infinitesimal.

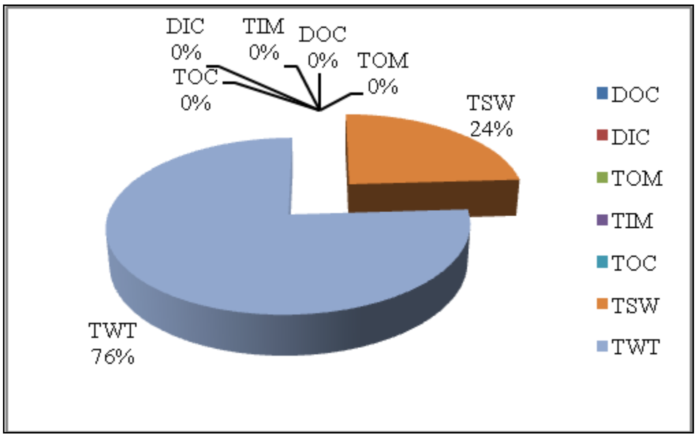

Figure 12: Percentage contribution to parameters of C to CO_2 sequestration and storage in sediment.

To the best of our knowledge, this is the first scientific study on the carbon sequestration potential of an aquatic system in Nigeria. Therefore, making comparisons with indigenous data from similar ecosystems to determine the performance of the studied ecosystem in carbon sequestration is difficult. However, the level of CO_2 sequestered in the study area is low when compared to levels recorded in relatively pristine environments (Santos et al., 2022). Although the Lagos Lagoon receives a lot of organic inputs from adjoining rivers, creeks, and runoffs, the ability of the system to accommodate and store these materials is hampered by the large-scale human activities taking place in the area, such as sand mining (Uwadiae and Felix, 2015). Other human activities including dumping of waste, boat transportation, bottom trawling, port activities, and diverse unsustainable environmental practices taking place in the lagoon may be blamable for the low CO_2 sequestration recorded. Based on Davidson and Janssens (2006), water column and sediment stability play a major role in supporting the storage of carbon in aquatic ecosystems. The low carbon sequestration recorded is expected due to the degraded nature of the area investigated.

The conditions necessary for the accumulation of carbon in water bodies include low water temperature and the predominance of fibrous vegetation (Davidson and Janssens, 2006). The rate of carbon accumulation depends largely on the quantity and quality of organic matter input. Other factors like altered salinity regime and extreme pH levels result in poor biomass production and reducion of organic matter. For example, the pH of aquatic systems is known to affect detrital formation. In a hgihly acidic or highly alkaline environment, the growing conditions for microorganisms are poor, resulting in low levels of biological oxidation of organic matter.

In the natural aquatic environment, without human disturbance, the biotic and abiotic components are in dynamic equilibrium (Yue et al., 2014). Organic matter in the aquatic system typically supports high biomass production and results in increased biological activity in the water column and at the sediment-water interface (Yue et al., 2014). Yang et al. (2021) and Yue et al. (2014) suggest that effective carbon sequestration and storage requires a rich cover of biofilm on the sediment-water interface. This biofilm, along with the sediment architecture, facilitates the capture and infiltration of water, protects the sediment, and supports decomposing organic matter, which provides an unbroken energy source for macro-, micro-, and meio-organisms. Additionally, well-aerated sediment at different depths allows effective distribution of nutrients and active interaction with microorganisms. The major period of nutrient release by microorganisms coincides with the major period of nutrient demand by benthic biota, leading to nutrient recycling by benthic organisms. This equilibrium creates a closed-cycle circulation of nutrients between sediment and the biota, as well as the overlying water, resulting in almost perfect physico-chemical conditions for biotic development through the bentho-pelagic coupling process (Santos et al., 2022). On the other hand, in anthropogically perturbed systems, this equilibrium is disrupted due to the distortion created by the unregulated use of aquatic environments for various human needs.

In order to improve the capacity of aquatic ecosystems for climate change mitigation, the IPCC (2019) recommends two management approaches. These approaches include: 1) regulating anthropogenic activities and adopting actions that maintain the integrity of natural carbon stores, thereby decreasing their potential release of greenhouse gases, and 2) encouraging actions that enhance the long-term removal of greenhouse gases from the atmosphere by aquatic systems. This can be achieved primarily through biological means, enhancing the natural carbon uptake of some aquatic habitats. This includes increasing their spatial coverage through habitat restoration and new habitat creation, as well as implementing management measures to maximize the carbon uptake and storage for existing coastal ecosystems.

CONCLUSIONS

This study is an eye-opener and a major breakthrough in the quest for indigenous data for computations of carbon sequestration and stock accounting in the Nigerian aquatic ecosystems. However, the limited scope and extent covered create the need for a more comprehensive invesitagtion to understand the lagoon’s full capacity for carbon sequestration and the roles played by various influencing factors.

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MAPPING COASTAL REGIONS OF GUINEA-BISSAU FOR ANALYSIS OF MANGROVE DYNAMICS USING REMOTE SENSING DATA

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KEYWORDS: mangroves, satellite image, cartography, mapping, GRASS GIS.

ABSTRACT

The study presents mapping of land cover changes in Guinea-Bissau using remote sensing data. Study area includes tidal floodplains of the rivers Geba, Caceu, and Rio Grande de Buba. Satellite images Landsat 8-9 OLI/TIRS were classified and analysed to evaluate landscape dynamics from 2017 to 2023. The methodology is based on GRASS GIS modules “i. cluster” and “i. maxlik” for image analysis. The results indicated variations in landscape patterns: decrease in natural forests, decline in mangroves, and expansion of urban and agricultural areas. The coastal region of Guinea-Bissau is one of the least known tropical ecosystems in West Africa, and it is among the most vulnerable African countries to climate effects. The paper contributes to the environmental monitoring of West African coasts.

RÉSUMÉ: Cartographie des régions côtières de la Guinée-Bissau pour l’analyse de la dynamique des mangroves à l’aide de données de télédétection.

L’étude présente une cartographie des changements de couverture terrestre en Guinée-Bissau à l’aide de données de télédétection. La zone d’étude comprend les plaines inondables des rivières Geba, Caceu et Rio Grande de Buba. Les images satellites Landsat 8-9 OLI/TIRS ont été classées et analysées pour évaluer la dynamique du paysage de 2017 à 2023. La méthodologie est basée sur les modules GRASS GIS “i. cluster” et “i. maxlik” pour l’analyse des images. Les résultats ont indiqué des variations dans les modèles de paysage: diminution des forêts naturelles, déclin des mangroves et expansion des zones urbaines et agricoles. La région côtière de la Guinée-Bissau est l’un des écosystèmes tropicaux les moins connus d’Afrique de l’Ouest et l’un des pays africains les plus vulnérables aux effets du climat. L’article contribue à la surveillance environnementale des côtes ouest-africaines.

REZUMAT: Cartografierea regiunilor de coastă din Guineea-Bissau pentru analiza dinamicii mangrovelor utilizând date de teledetecție.

Studiul prezintă cartografierea modificărilor acoperirii terenurilor din Guineea-Bissau folosind date de teledetecție. Zona de studiu include luncile afectate de maree ale râurilor Geba, Caceu și Rio Grande de Buba. Imaginile din satelit Landsat au fost clasificate și analizate pentru a evalua dinamica peisajului din 2017 până în 2023. Metodologia se bazează pe modulele GRASS GIS pentru analiza imaginii. Rezultatele au indicat variații ale modelelor de peisaj: scăderea pădurilor naturale, scăderea mangrovelor și extinderea zonelor urbane și agricole. Regiunea de coastă a Guineei-Bissau este unul dintre cele mai puțin cunoscute ecosisteme tropicale din Africa de Vest și se numără printre cele mai vulnerabile țări africane la efectele climatice. Lucrarea contribuie la monitorizarea mediului pe coastele Africii de Vest.

INTRODUCTION

Background

In recent decades, large-scale environmental problems, including deforestation, soil erosion, and overgrazing, have attracted international attention to Guinea-Bissau. Extensive conversion of salt marshes, forests, and mangroves to agricultural and urban lands is impacting land cover types in the country's coastal regions (Cabral and Costa, 2017) and affecting landscape configuration (Vasconcelos et al., 2002). Mapping land cover changes provides crucial information that supports solving such issues through visualization and spatial analysis. Maps create necessary basis for the development of practical measures aimed at reducing the effects of climate change or human activities. Additionally, maps assist in evaluation of the effectiveness of current agricultural policies and identifying land management changes. Therefore, land cover mapping has become a subject for environmental monitoring as an effective approach to detect vulnerable areas.

Remote sensing (RS) offers crucial data that facilitates decision-making and aids in striking a balance between forest conversion and land use development. Comparison of multi-temporal satellite images enables to highlight trends in landscape dynamics. Such approach helps determine what changes are needed for nature protection and tracks the advancement of current regulations on maps created using spaceborn data. Environmental monitoring supported by RS data is especially crucial in vulnerable landscapes of African regions for planning mitigation and adaptation measures, as well as nature conservation and protection. Moreover, lack of datasets and non-accessible regions in West Africa make the use of satellite images crucial for exposing patterns of land cover types.

With this regard, using RS data for landscape mapping has grown in importance over the past few years as a source of data for environmental and climate research in West Africa. When satellite imagery, and sophisticated processing tools are combined, this kind of information becomes even more pertinent. This necessitates precise reporting of environmental variables (Cabral et al., 2010). At the local, regional, and global levels, changes in land cover have been identified and tracked using a variety of RS data (Dao, 2021). Change detection seeks to detect variations in satellite images between two or more dates, classify the changes, and measure their magnitude. For effective land cover change identification, a variety of computer vision approaches have been developed (Mainguet, 1990). Certain techniques, including image comparison, rationing, or principal component analysis methods (Sharma et al., 2023; Joly et al., 1983), are used to detect changes in the landscape. Nevertheless, the automated comparison of several satellite images is required for comprehensive information on land cover changes.

Traditionally, methods of landscape monitoring compare maps created using supervised human classification to identify specific changes in land cover between satellite images taken at two different dates (Géroyannis, 1984). However, putting such a system in use necessitates separate training grounds and frequently a priori familiarity with the surrounding environment. Since the beginning of satellite missions in the 1970s, satellite images and RS data have been used intensively in environmental and ecological research (Alam and Hossain, 2024; Jombo and Adelabu, 2023; Lavanya et al., 2023; Lemenkova, 2020; Heymann, 1978). In brief, Regrain (1982) summarized the cases using satellite image processing in geographical research throughout this time. The fact that RS data has been continuously used for environmental monitoring over the past 50 years attests to its worth and use as a source of data for geographical research.

Nowadays, satellite imagery presents the most effective source of geospatial data which is actively used for environmental analysis and landscape mapping (Lemenkova, 2024a, b, 2023a, b; Tang et al., 2023). For instance, landscape changes in tropical forests in Africa can be detected using satellite images (Lemenkova, 2024c; Cabral, et al., 2010; Bruneau and Kilian, 1984). Example of multispectral satellite images is presented with Landsat which enable the identification of objects by the light reflected by the Earth's surface. More specifically, satellite images contain information on spectral reflectance of the objects which shows how a surface responds when exposed to the sun's beams through the distinction between the objects that absorb solar radiation and reflect it back to space. The reflected part is the one that is recorded by satellite sensors and used to obtain information for mapping. This fundamental property of RS data enables to use them as a source of information for environmental monitoring and mapping.

Objective and goals

The primary goal of this work is to use the GRASS GIS software's programming method for satellite image processing to address the aforementioned issue of environmental monitoring in Guinea-Bissau region of West Africa (Fig. 1).

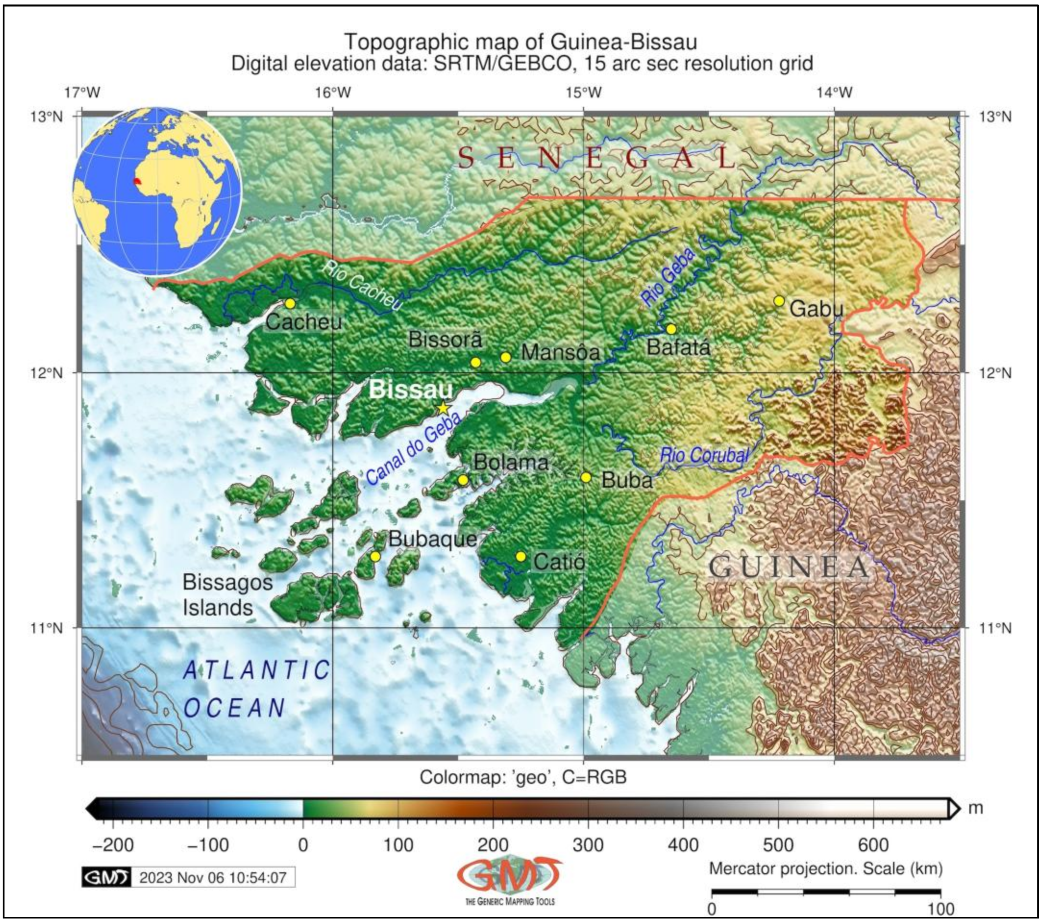

Figure 1: Topographic map of Guinea-Bissau, West Africa.

Using GRASS GIS modules and a scripting approach, a set of Landsat OLI/TIRS images is processed. By employing computer vision techniques to determine the spectral reflectance of the pixels on the images and cluster them into distinct categories, this method automatically performs identification of land cover types. The coastal region of Guinea-Bissau is one of the least known tropical ecosystems in West Africa due to the lack of existing studies. Besides, with regard to the effects of climate change, it is among the most vulnerable and threatened African countries. Such characteristics of the country require additional efforts on environmental monitoring. With this regard, this study contributes to cover the existing lacks in studies on Guinea-Bissau through presented cartographic data processing.

This work provides a machine classification based on the algorithms of computer vision that automatically recognize spectral reflectance at the pixel level, representing landscape dynamics objectively and independently from existing methods. In this study, scripts – a programming technique to geographic data processing – are used as an alternative to current GIS approaches for processing and classifying RS data. Three processed satellite images were used to create map time series in order to accomplish these goals. The primary cover class transitions identified in this study were the development of secondary vegetation and increased agricultural area in place of the loss of intact mangrove forests. According to relevant studies (Carreiras et al., 2012), these transformations align with the primary resource exploitation patterns in the coastal regions (Fig. 1).

There is a fundamental difference in the way that information is extracted between what is classified as satellite images and cartographic data. In traditional cartography, where raw data is used without software processing, visualization is more straightforward, whereas processing data from RS requires more sophisticated technical algorithms. The data retrieved by RS, on the other hand, accurately depicts the terrain. However, RS has certain limitations that can be introduced during the pre-processing, digital and visual classification, rectification to real-world coordinates, post-processing, and registration to other images (Girou et al., 1998; Desjardins and Cavayas, 1991). For these reasons, it is necessary to use advanced image processing methods such as GRASS GIS software that allows for accurate processing and analysis of RS data through the use of special modules and scripts.

This study uses Landsat satellite images from 2013 to 2023 to identify changes in tidal floodplains and mangroves on the coastal regions of the Geba, Caceu, and Rio Grande de Buba rivers. In particular, the research set out to: (1) Create land cover maps by interpreting and classifying Landsat OLI/TIRS satellite images spanning six years, from 2017 to 2023; (2) Use these maps to quantify and visualize dynamic changes in vegetation cover; and (3) Assess the accuracy of digital classification for mapping vegetation in the floodplains and coastal zone. In order to classify and visually interpret the data, the images were digitally processed using scripting algorithms. To assess future changes in land cover types, cartographic data regarding the land cover distribution is necessary. In this study, several land cover maps are made using GRASS GIS, a freely available software for mapping. The maps were created using RS data in order to obtain accurate visualization of land cover types. In this way, this paper contributes to the advancements in Earth system science on a regional scale of Guinea-Bissau.

Study area

The study area is located in the western coastal region of Guinea-Bissau, on the Atlantic coast (Figs. 1 and 2). Geographically, Guinea-Bissau is situated on the west coast of Africa approximately between latitudes 10.5°-13.0°N and longitudes 13.5°-17°W. It spans over 36,125 km^2 of total area and consists of the continental mainland and a group of islands comprising the Bijagós Archipelago. The environmental vulnerability is caused by its flat topography and vast meandering coastal zone which is composed of several rivers flowing into the Atlantic Ocean. Besides, ocean tides contribute to local flooding (Temudo et al., 2022). Recent studies (Lopes et al., 2022) reported regarding the ecological vulnerability of Guinea-Bissau's coastal regions.

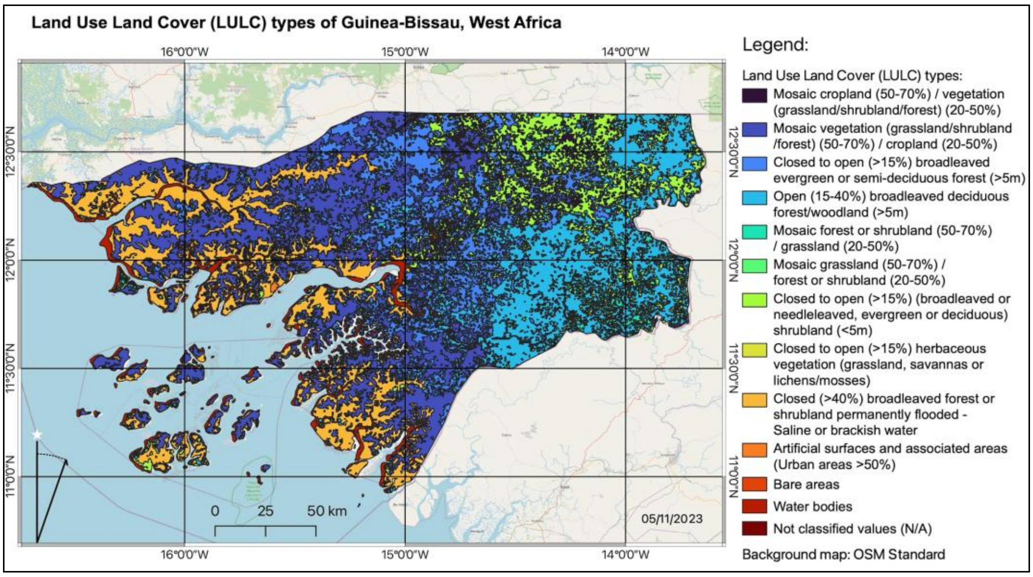

Figure 2: Map of land use types in Guinea-Bissau, West Africa. Data: Food and Agriculture Organisation (FAO). Map source: author. Software: QGIS.

Guinea-Bissau is characterized by contrasting geographical areas and biogeographic regions (Catarino, 2004). From the one part, there are coastal lowland areas, consisting largely of mangroves and swamps stretching from north to south and mainly by a flat land surface with altitudes below 100 m. From the other side, there are areas with forests dominating in the southwest and inner regions of the country. Savanna woodland is present in the northern and eastern regions. Comparison of such varied and contrasting areas enables to support studies of landscape patterns and better analyse landscape dynamics in similar regions of West Africa.

According to Andreetta et al. (2016), Guinea-Bissau is notable for landscape diversity. It comprises a variety of land cover types, including such contrasting classes as mangrove forests, broadleaved forests, flooded forests, grasslands, and urban areas. Agricultural activities in the country are regulated by variations in temperature and the occurrence of wet seasons that alternate with periods of hot, dry winds coming from the Sahara. Changes in land cover types are linked to the intensive agricultural activities (Temudo and Abrantes, 2014) and climate impacts (Dieng et al., 2018). Rising temperatures in the interior regions and periods of drought lead to desertification (Ickowitz, 2006).

In coastal areas, additional impacts on landscape dynamics include the growth of the submerged vegetation, i.e., mangroves. Mangrove habitats are located on the floodplains of the river deltas along the Atlantic coasts and experience the influence of tidal fluctuations related to moon phases, which cause local floods and inundations. The coastal region situated near the Geba River's mouth is characterized by the impacts from its hydrology and effects of coastal circulation and tides. Here, the important role plays the tidal regime. Tides are typically along the Atlantic coast and the location of river estuary has an impact on the distribution of vegetation in the lagoons along with impacts of salt water from the ocean (Catarino et al., 2002). For example, wet monsoon season, which lasts from June to October and brings heavy rains and hot, humid weather, is different from the dry season, which runs from November to May in tropical environment. Such variations in rainfall regimes between the north and south and east and west affect soil qualities, which influence landscape patterns in Guinea-Bissau.

MATERIAL AND METHODS

Characterizing and assessing spatial phenomena by any of the conventional GIS methods, such as cartographic map analysis, requires many efforts. There are benefits and drawbacks in using different GIS to evaluate landscape diversity and its spatial organization. The primary benefits of GRASS GIS, in contrast to more conventional tools, are its strong programming functionality, advanced tools for RS data processing, and diverse embedded algorithms for geospatial calculation that may be applied to determine the topology, structure, and relationships among landscape elements. Therefore, the programming tools of GRASS GIS software have been used to analyze the landscapes of Guinea-Bissau. Furthermore, this paper outlines a method for integrating geospatial data from several sources for landscape analysis and evaluate environmental dynamics. A novel workflow technique for processing data from RS and mapping is provided by the scripting approach which includes image processing, visualization, and classification.

Data

The data used in this study include Landsat images from May 7, 2023, May 6, 2020, and April 28, 2017, as shown in natural colors (Fig. 3). The data were obtained from the USGS Open Repository where RS data are publicly available from the EarthExplorer archive. To lessen the noise from clouds and atmospheric effects, the data were filtered. For every image, the cloudiness percentage is less than 10%. The images were taken at the end of the dry season. Cloud cover is usually minimal during this time, but the vegetation is distinct from all other land cover types due to vivid green color.

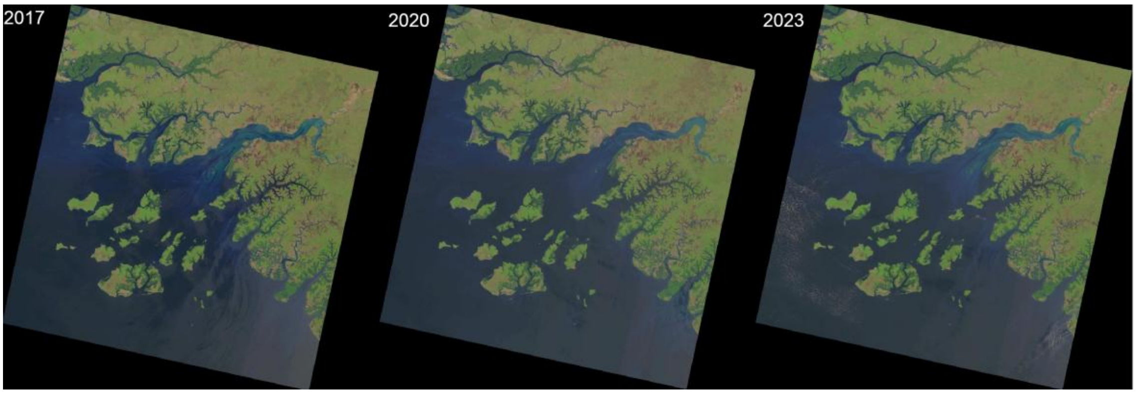

Figure 3: The color composite images over Guinea-Bissau, West Africa. Data source: USGS. Images were taken on May 7, 2023, May 6, 2020, and April 28, 2017.

Geospatial data enable effective environmental monitoring of Guinea-Bissau and provide the basis for sustainable development, ecological planning, and natural resource management. Landscape change analysis based on satellite images is a technique that performs a comparison between land cover types using multi-temporal images. Comparative analysis of maps created using classified images allows for the detection of landscape changes (Pennober, 2003). The Landsat images were used due to their effectiveness. Literature has provided a description of the significance of multispectral Landsat data among the other RS data for environmental studies. Studies using Landsat for mapping coastal West Africa are reported (e.g., Lemenkova, 2024a; 2022; Lahuec et al., 1992). Besides, they are employed to record the processes of land cover change and deforestation in Guinea-Bissau (Cuq et al., 1996).

Methods and techniques

The digital image processing used to create a land cover map from Landsat OLI/TIRS imagery was performed in six steps using the techniques of GRASS GIS: 1) image import, 2) data mining and analysis, 3) image classification, 4) image post-processing, 5) mapping, and 6) accuracy assessment. Landsat images were geometrically rectified to EPSG coordinates: 2095, Universal Transverse Mercator (UTM) zone 28N in Guinea Bissau. Satellite images of different dates were classified independently and then the classified images were compared for the years 2017, 2020 and 2023 (Fig. 3). The comparative analysis is based on the values of the individual pixel spectral reflectance on the multi-temporal images. Analysis of changes on the classified images of different dates shows the dynamics of the landscape.

Optimal Landsat band combinations were selected and used for creating false and true color composites (bands 4-3-2, 2-3-4, and 7-6-4 as Red-Green-Blue) and Shortwave Infrared (SWIR2, SWIR1, Red), to ease the processing of the data. Bands 4 (red), 3 (green), and 2 Near Infrared (NIR) produced the best separation for mangroves, tropical forests, agricultural lands, urban regions, and coastal areas. The appropriate modules were applied for color composites and contrast stretching techniques to process multispectral bands (Fig. 4).

Afterwards, unsupervised automatic classification with a variable number of clusters was carried out using module “i.cluster”. To statistically assess the accuracy of the land cover maps, the classification algorithms for each image were assessed by creating error matrices and carrying out a Kappa analysis. It is difficult to identify the vegetation types due to similarities in spectral reflectance of different plants that cause spectrum confusion. Therefore, the automatic approach of GRASS GIS was used for vegetation mapping. Since the data do not follow a normal distribution, Landsat images were processed using a computer vision approach based on automated clustering to increase the classification accuracy. This enabled to categorize various land cover types. The maps were created to show landscape dynamics in Guinea-Bissau. Color composites were used from the multispectral bands. Spectral discrimination and spatial analysis were used to examine the images and identify contrasting land cover types: mangrove forests in the coastal areas, inner regions, water, urban areas, etc.

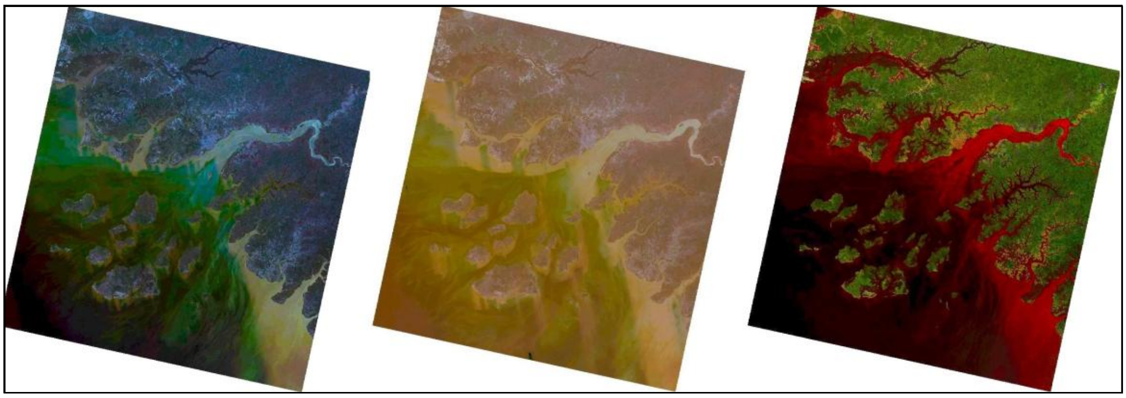

Figure 4: True and false colour composites of Landsat 8-9 OLI/TIRS images (bands 4-3-2, 2-3-4 and 7-6-4), Guinea-Bissau for the years 2017, 2020 and 2023.

RESULTS

The results include three maps of the major categories of land cover which were identified prior to digital classification. These include mangroves, estuaries, cities, and tropical forests, as major categories, as well as minor categories. In total, 12 classes were identified and verified using the unsupervised classification of the satellite images: 1) deep water (ocean); 2) shallow water (shelf); 3) wetlands permanently flooded by saline or brackish water; 4) grasslands; 5) mosaic croplands and agricultural fields; 6) bare soil; 7) coastal mangrove forests; 8) broadleaved evergreen semi-deciduous forests; 9) savannah and shrubland; 10) artificial surfaces (urban and industrial areas); 11) herbaceous vegetation (lichens, mosses, and grassland); 12) woodland and broadleaved deciduous forest (Fig. 5).

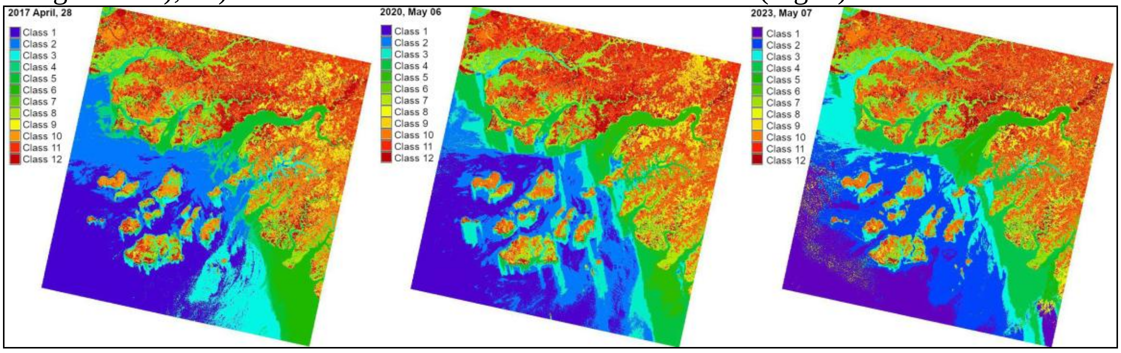

Figure 5: Results of land cover type maps derived from the Landsat 8-9 OLI/TIRS image classification for Guinea-Bissau in the years 2017, 2020, and 2023.

In order to identify 12 common classes for the comparisons, the map legends were combined into a similar nomenclature and color palette. The findings indicate significant variations in the patterns that have been seen in agricultural regions and coastal areas.

There are distinctions between various land use or land cover types. For instance, coastal areas and water surfaces were dark colored. The colors of the salt flats combined with fresh water from the estuaries of the Geba, Corubal, and Rio Grande de Buba rivers are paler than those of the sea. Figure 5 shows how diverse types of vegetation, like mangroves, deciduous forests or woodlands, scrub, and evergreen deciduous forests, exhibit stronger spectral signals and appear in different colors of green. Due to such differences and similarities in their signatures, selected classes have distinct colors, for instance: mosaic vegetation, flooded shrublands and deciduous forests around the Atlantic coasts or estuaries appear dark green. This enables to distinguish these classes from the others which also have a greenish hue. Mangrove plants belong to the same class as flooded estuarine vegetation and show no clear differences from one to another while partially submerged in water (areas colored by cyan).

The results of the classification and validation of the acquired map and images are presented as short-time series (Fig. 5). Color composites made of few multispectral bands are produced. The studied region was analysed for landscape dynamics. The results were: (1) mapping changes in land cover types, with a focus on deforested areas and (2) numerical analyses of changes in land cover types by computed pixels that are associated to each of the 12 classes of Landsat bands for each period (2017, 2020, and 2023); (3) analysis of dynamics in mangrove-covered coastal areas; (4) evaluated the technical feasibility of using GRASS GIS to create land cover maps using moderate resolution (30 m) satellite images Landsat-8 OLI-TIRS. For validation of results, data from the Food and Agriculture Organization (FAO) were used to identify the distribution of land cover types over the studied area. Table 1 shows the calculations of the averages for estimated bands and values for 2017, 2020 and 2023.

Table 1: Calculated values of land cover classes and class means for spectral band Landsat-8 OLI/TIRS. Designations for each band in different wavelengths in the electromagnetic spectrum: Band 1 – Coastal aerosol; Band 2 – Blue; Band 3 – Green; Band 4 – Red; Band 5 – Near Infrared (NIR); Band 6 – Shortwave Infrared (SWIR) 1.

Class	1	2	3	4	5	6	7	8	9	10	11	12
2017	1409	782	537	388	262	327	273	415	369	882	838	438
2020	1105	1120	590	420	438	401	278	100	103	310	468	1589
2023	1203	1065	505	410	440	316	342	138	111	300	603	1509
2017: Class means for each spectral band Landsat-8 OLI/TIRS												
Class	1	2	3	4	5	6	7	8	9	10	11	12
Band 1	7168.48	7617.39	7807.68	8743.92	9897.9	10707.3	8339.52	8198.18	8712.04	8163.95	8543.99	9436.27
Band 2	7700.22	8565.77	8498.15	9545.6	10586.7	11318.8	8770.28	8567.47	9021.95	8461.13	8907.31	9909.03
Band 3	8487.14	10037	9556.42	10868.4	11761	12211.4	9765.21	9583.75	9879.16	9599.46	10028.8	11163.6
Band 4	7658.64	8784.82	8747.36	10311.1	11478.2	11683.4	9770.55	9434.03	10341.6	9371.5	10481.5	12323.2
Band 5	7469.59	7344.08	8560.73	8658.68	9842.98	10868.6	12326.6	14233.5	14109.1	17600.9	16919	16633.3
Band 6	7862.61	7745.24	8818.03	8289.35	8726	10100.1	10468.6	11113.4	15319.1	14055.6	16923	19889.4
2020: Class means for each spectral band Landsat-8 OLI/TIRS												
Class	1	2	3	4	5	6	7	8	9	10	11	12
Band 1	7104.73	7455.29	8500.93	10002.1	10510	8422.6	8203.68	8708.72	9007.16	8187.9	8468.11	9550.18
Band 2	7819.79	8394.61	9358.91	10665.2	11240.1	8954.71	8642.96	9093.69	9409.26	8570.29	8915.8	10059.7
Band 3	8870.45	9823.02	10604.2	11629.1	12514.1	10051.5	9716.14	10014.2	10394.1	9807.74	10181.2	11384.3
Band 4	7844.29	8583.5	9624.92	10875.9	12439.7	10008.8	9554.35	10362.6	11048.1	9600.86	10597.9	12471.5
Band 5	7669.29	8053.91	8770.81	9531.95	10873.6	11718.6	13927.6	13601.6	15040.9	17586.4	17243.2	16944.1
Band 6	8190.72	8555.73	8761.31	9067.82	9575.67	10104.1	10965.4	14153.5	17029.4	14172.6	16750.6	19700.6
2023: Class means for each spectral band Landsat-8 OLI/TIRS												
Class	1	2	3	4	5	6	7	8	9	10	11	12
Band 1	6962.37	8161.88	9118.64	10772.7	11365.2	8740.46	8624.57	9106.88	9354.15	8460.79	8779.7	10154.2
Band 2	8305.26	9469.5	10555	11764.7	12808.7	9889.92	9687.4	10159.3	10388.5	9703.08	10011.1	11470.2
Band 3	7724.79	8350.57	9477.81	11017.6	12971.9	9787.43	9479.7	10411.1	11004.3	9362.82	10207.4	12572.7
Band 4	7936.78	8095.7	8506.35	9718.46	11490.8	11764.6	14237.6	13364.9	15509.6	17907.5	17319.6	16945.2
Band 5	8520.91	8575.67	8658.14	9219.97	9530.32	10149	10976.4	13620	17188.5	13912.2	16008.8	19972
Band 6	8384.81	8440.37	8450.52	8843.81	9072.77	9085.19	9248.41	11874.6	14043.3	10562.5	12365.5	16577.5

Changes in the land cover types in Guinea-Bissau's coastal region were identified and visualized in the target landscapes from 2017 to 2023. In particular, by identifying distinct land cover patches, the satellite images Landsat OLI/TIRS taken at various periods were compared to evaluate the dynamics of diverse land cover types. For instance, for forest class 8 (broadleaved evergreen semi-deciduous forests) the highest variation is found in comparison of images followed by class 12 (woodland and broadleaved deciduous forest) as well as class 3 wetlands permanently flooded by saline or brackish water. Degradation of mangrove areas in Guinea-Bissau is mainly caused by the following factors. First, deforestation is mainly caused by extensive and excessive commercial logging. In addition, uncontrolled artisanal mining, unsustainable logging operations, conversion of forest to agricultural plantations and harvesting of wood for construction and firewood are the other drivers of deforestation in Guinea-Bissau. For class 9 (savannah and shrubland), all maps show a slightly negative variation in distribution of pixels and their assignment to this class. Evergreen or deciduous shrubs with needle-like leaves can be recognized in every shot thanks to a unique spectral signature. Due to spectrum reflection effects and this vegetation type's high backscatter coefficients, they look light in color.

Relatively to grassland class, the obtained maps show negative values, which means the increase of this land class, when comparing with the respective reference map (FAO, Fig. 2). Also, the class 5 (mosaic croplands and agricultural fields) and class 6 (bare soil) both show the trend of increase in values. This indicates the expansion of the agricultural activities and replacement of natural vegetation types through artificial types and land occupied by cultivation and agriculture. Furthermore, small-scale saw-milling for local markets and firewood production are additional triggers of deforestation, as are mining, both commercial and artisanal. Finally, social drivers of deforestation in Guinea-Bissau include processes related to post-conflict population migrations, which lead to additional clearing for agriculture. This includes, for example, the cutting down of forests during clearing for the conversion of land to agriculture, particularly dry rice cultivation.

Woods, mangroves, agricultural land, mudflats, and wetlands in drylands and coastal areas were identified as the principal land cover types that were found. Moreover, the calculations were also performed to evaluate landscape dynamics by comparing and estimating the areas covered by various land cover types. The computed number of pixels attributed to each land cover class for three different years is included in table 1 for comparison of changes. Forests and mangroves were evaluated for regression and progression using numerical calculations of landscape fragments, and the results were presented in cluster reports that indicate which land cover categories are increasing and which are decreasing. The total area of the 12 aggregated classes derived from the comparison of each map obtained from processed satellite images is shown in table 1, as well as variations by multispectral bands.

Figure 6 presents the accuracy assessment that evaluates the cartographic results. For each of the three satellite images, it displays the likelihood that each pixel is assigned correctly to the appropriate class. The comparison of maps obtained on different years for accurate analysis and evaluation of land cover changes is ensured by the geographical correspondence of the satellite images that cover the same area. Clustering-based classification demonstrated the overall accuracy of Guinea-Bissau maps of 2017, 2020, and 2023 for a convergence of 98.1%, 98.2%, and 98.1%, respectively. This demonstrated a high mapping accuracy based on the processing of remote sensing data by GRASS GIS. The coverage of natural vegetation, such as woods, mangroves, shrubs, and grasses, has declined while that has built-up areas and other vegetation types has increased, according to a comparison of the classed maps.

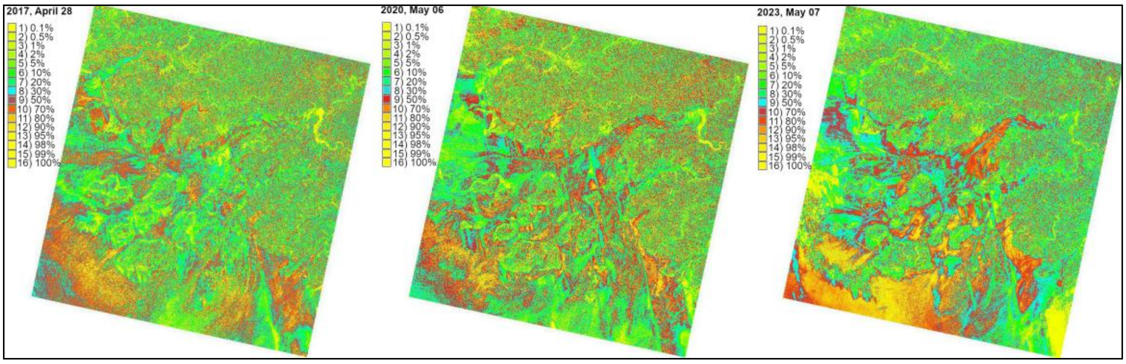

Figure 6: Estimation of pixel confidence levels with rejection probability values for Landsat 8-9 OLI/TIRS images, Guinea-Bissau (2017, 2020, and 2023).

The results of the statistical assessment of the accuracy of the land cover mapping are presented in figure 7 based on the evaluated accuracy of the classification algorithms for each image, including error matrices and Kappa analysis.

```
########## final results #############
12 classes (convergence=98.1%)

class separability matrix

       1    2    3    4    5    6    7    8    9   10

 1     0
 2   1.2    0
 3   1.5  1.2    0
 4   2.4  1.3  1.2    0
 5   3.8  2.7  2.3  1.0    0
 6   4.6  3.9  2.9  1.9  1.0    0
 7   2.5  2.3  1.4  1.4  1.7  2.0    0
 8   3.5  3.4  2.2  2.2  2.4  2.6  0.5    0
 9   4.0  3.8  2.7  2.6  2.5  2.7  1.4  1.5    0
10   4.5  4.4  3.2  3.2  3.2  3.3  1.5  1.2  1.1    0
11   5.7  5.4  4.0  3.7  3.5  3.6  2.1  2.1  0.6  1.2
12   5.0  4.8  3.8  3.5  3.0  2.9  2.4  2.6  1.3  2.0

      11   12

11     0
12   1.2    0
```

```
########## final results #############
12 classes (convergence=98.2%)

class separability matrix

       1    2    3    4    5    6    7    8    9   10

 1     0
 2   0.9    0
 3   1.9  1.1    0
 4   3.4  2.6  1.3    0
 5   4.3  3.5  2.1  0.9    0
 6   2.4  1.7  1.2  1.6  2.0    0
 7   3.2  2.4  2.0  2.6  2.9  0.8    0
 8   3.5  2.9  2.4  2.5  2.7  1.5  1.4    0
 9   5.0  4.2  3.7  3.3  3.3  2.6  2.6  0.9    0
10   4.5  3.7  3.3  3.5  3.5  2.0  1.5  1.0  1.5    0
11   5.5  4.6  4.0  3.9  4.0  2.7  2.4  1.0  0.7  1.1
12   4.8  4.3  3.8  3.4  3.2  2.9  2.9  1.6  0.9  1.9

      11   12

11     0
12   1.2    0
```

```
########## final results #############
12 classes (convergence=98.1%)

class separability matrix

       1    2    3    4    5    6    7    8    9   10

 1     0
 2   0.8    0
 3   1.5  1.0    0
 4   2.6  2.3  1.2    0
 5   3.6  3.4  2.1  1.0    0
 6   1.9  1.5  1.1  1.5  2.0    0
 7   2.9  2.4  1.9  2.4  2.6  0.7    0
 8   2.6  2.4  2.0  1.9  1.9  1.1  1.2    0
 9   4.2  4.0  3.4  3.2  2.7  2.3  2.5  1.0    0
10   4.1  3.6  3.1  3.7  3.3  1.8  1.4  1.0  1.6    0
11   4.7  4.4  3.6  3.8  3.2  2.3  2.2  1.0  0.8  1.0
12   4.4  4.3  3.7  3.4  2.7  2.8  2.9  1.6  0.9  2.2

      11   12

11     0
12   1.5    0
```

Figure 7: Values for the rejection probability and estimated pixel confidence levels for Landsat 8-9 OLI/TIRS images for the years 2017, 2020, and 2023.

The results show that the areas of mangroves and those of drylands in Guinea-Bissau are increasing. The areas covered by land cover types are reported in details in the available GitHub repository: https://github.com/paulinelemenkova/Guinea-Bissau-GRASS-GIS.

DISCUSSION

Environmental development and heritage are reflected in landscape history. Extracting information about the types of land cover changes from the satellite images over time can help explain past events and increase the knowledge on the environmental evolution. Climate-related problems (desertification, erosion, fragmentation of the landscape, degradation of the coasts, and deforestation) raise environmental concerns. Urbanization and intensive agriculture are two examples of anthropogenic activities that trigger these and related processes.

In this work, a programming framework for satellite image processing using GRASS GIS was created using the author's GitHub repository which has made the scripts available for reuse and reference. Besides, the results of image processing are reported in year's tables (2017, 2020, and 2023) and provide a summary of the classification findings for each image. Using the coastal region of Guinea-Bissau, West Africa, as an example, the given scripting technique can be used to achieve real-time change detection for environmental monitoring of African landscapes.

The contribution of this paper can be summarised in: 1) application of advanced technical cartographic methods for satellite image processing and 2) environmental analysis of Guinea-Bissau region using land cover analysis supported by remote sensing. While traditional GIS have limited landscape analysis capabilities and lack essential tools for complex calculations, GRASS GIS algorithms allow performing spatial analysis of landscape structure at an advanced level. In particular, the use of scripts to analyze land use, deforestation and landscape fragmentation from satellite image processing offers the advantage of rapid mapping.

Remote sensing data have been used to analyze these changes in landscape, providing insight into the complexity of tropical forests and coastal areas. Satellite images can be used to obtain the information of landscape development. Although the information is concealed in remote sensing data, but it becomes visible once the images are processed and analyzed with the use of spatial analysis tools. This article proved that GRASS GIS is effective in extracting such information from the satellite image for explaining the landscape dynamics. Using satellite data, one can map past landscapes, forecast potential dynamics, and evaluate the rate at which different types of land cover are changed using various mapping approaches.

For ecological research, environmental mapping, and the prediction of potential changes in coastal areas, accurate mapping and visualization of land cover changes are essential. This study showed how environmental dynamics along Guinea-Bissau's coasts can be analyzed using image processing techniques. The sophisticated method for processing satellite images and reliably mapping changes in the landscape is responsible for the results, which agree with those of earlier research. In a technical sense, we demonstrated that the modules can reliably estimate changes in land cover based on picture analysis and classification. Through the mapping and environmental monitoring of land cover types detected in the satellite images, remote sensing makes it possible to document changes in the environment. To record changes in the types of land cover, many methods are employed for image processing and the mapping that follows. In this study, we used GRASS GIS modules designed for image processing, visualization, and cartographic representation.

CONCLUSIONS

This study demonstrated the effectiveness of the scripting techniques applied for processing time series analysis of satellite images. Such integration of data and methods offer the most reliable means of environmental and ecological research. Specifically, it enables to monitor ecosystems preserving a historical record of the landscape and illustrating changes in land cover over time. A precise and sophisticated tool for environmental mapping and monitoring is also provided by GRASS GIS software, which has numerous map visualization and image processing modules. Employing satellite images as a source of data shows that remote sensing effectively supports environmental monitoring and thematic mapping.

Technically, this study also demonstrates how the suggested GRASS GIS software tools have been successfully used to monitor Guinea-Bissau's land cover and assess the short-term dynamics of the landscape over the last five years (2017-2023). This approach is transferable to different time periods and geographical areas. Using GRASS GIS software, the image processing approach combines a module-based classification methodology to generate unique maps of land cover change with an accuracy assessment following classifications to validate the outcomes. Environmental monitoring of coastal landscapes reveals connections between the spatial structure of coastal landscapes (heterogeneity, connectedness, and fragmentation) and landscape ecology (matrix and corridors). A useful technique for analyzing the dynamics in ecosystems is cartographic integration. The dynamics of African forests and land cover changes are influenced by complex character of landscapes and their interactions with other environmental parameters, such as temperature and hydrology.

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A COMPREHENSIVE STUDY OF ASSESSING WATER QUALITY AND PHYTOPLANKTON COMMUNITIES IN THE RIVER RAVI (INDIA)

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KEYWORDS: water quality, phytoplankton, anthropogenic activity, sustainability.

ABSTRACT

Due to anthropogenic activities, the water quality of freshwater bodies is rapidly decreasing. The aim of this study was to assess the water quality and phytoplankton diversity in the upper Ravi River basin between September 2022 and August 2023. Overall, the water quality was within the allowable limits, but in sampling zone 3, there was a deteriorating trend in certain physicochemical parameters, including turbidity, dissolved oxygen, and biological oxygen demand during monsoon months. Bacillariophyceae (11 genera) was the most dominant group followed by Chlorophyceae (8 genera). A total of 23 different genera of phytoplankton were observed. It can be concluded that human activities, such as mining in riverbeds, and the construction of dams and barrages, have a direct impact on water quality and phytoplankton diversity. These activities need to be monitored on a regular basis.

RÉSUMÉ: Étude approfondie de l'évaluation de la qualité de l'eau et des communautés de phytoplancton dans la rivière Ravi (Inde).

En raison des activités anthropiques, la qualité de l'eau des masses d'eau douce diminue rapidement. L'objectif des recherches actuelles était d'évaluer la qualité de l'eau et la diversité du phytoplancton dans le bassin supérieur du fleuve Ravi, entre septembre 2022 et août 2023. Dans l'ensemble, la qualité de l'eau était dans la limite autorisée, mais dans la zone d'échantillonnage 3, il y avait une tendance à la détérioration. Certaines mesures physico-chimiques, notamment la turbidité, l'oxygène dissous et la demande biologique en oxygène pendant les mois de mousson. Les Bacillariophyceae (11 genres) constituaient le groupe le plus dominant, suivi des Chlorophyceae (8 genres). Au total, 23 genres différents de phytoplancton ont été observés. On peut conclure que les activités humaines, telles que l'exploitation minière des lits des rivières, la construction de digues et de barrages, ont un impact direct sur la qualité de l'eau et la diversité du phytoplancton. Ces activités doivent être surveillées régulièrement.

REZUMAT: Un studiu comprehensiv de evaluare a calității apei și a comunităților de fitoplancton din râul Ravi (India).

Datorită activităților antropice, calitatea apei din corpurile de apă dulce scade rapid. Scopul cercetării actuale a fost acela de a evalua calitatea apei și diversitatea fitoplanctonului în bazinul superior al râului Ravi, în perioada septembrie 2022 – august 2023. În general, calitatea apei a fost în limitele admise, dar în zona de prelevare 3 a existat o tendință de deteriorare a anumitor parametri fizico-chimici, inclusiv turbiditatea, oxigenul dizolvat și cererea biologică de oxigen în lunile cu muson. Bacillariophyceae (11 genuri) a fost grupul dominant, urmat de Chlorophyceae (8 genuri). Au fost observate un total de 23 de genuri diferite de fitoplancton. Se poate concluziona că activitățile umane, cum ar fi mineritul în albiile râurilor și construcția de baraje, au un impact direct asupra calității apei și diversității fitoplanctonului. Aceste activități trebuie monitorizate în mod regulat.

INTRODUCTION

Freshwater ecosystems offer essential services to humans, including the generation of nutritional resources, the purification of water, recreational opportunities, and on a more global scale, the management of climate (Oberdorff, 2022). Rivers are the most dynamic natural water resource and an integral component of the freshwater environment, and rivers support a wide range of development-related activities (Antonelli et al., 2024; Vári et al. 2022; Boretti and Rosa, 2019), this is the situation in India too (Rumana et al., 2015; Jeeva et al., 2011)

Phytoplankton is considered a bioindicator because of its brief life cycle and rapid reaction to alterations in water quality, particularly in river ecosystems (Zhang et al., 2021).

Moreover, the presence of manufacturing, farming, and anthropic operations near the river inevitably leads to alterations in the quality of water (Cahyonugroho et al., 2022). In addition to removing nitrogen and ammonia from the water for growth, phytoplankton also plays a significant role in reducing the amounts of potentially harmful metabolites (Dembowska, 2021). Microorganisms, unicellular organisms, and phytoplankton generate their food photoautotrophically in aquatic environments. The overall nutrient cycles of any freshwater ecosystem depend on phytoplankton (Mitra and Leles, 2023; Kumar et al., 2023).

Plankton are sensitive to changes and disturbances that occur in their surrounding environment and quickly react to any disruption created (Chandel et al. 2023; Mishra et al. 2021; Bilous et al., 2013). They support the food net by acting as the primary food source in the freshwater. According to Zhang et al. (2021), water quality characteristics play a crucial role in controlling the distribution of phytoplankton in freshwater ecosystems. Yang et al. (2021) assert that rivers are of the highest importance among all the natural resources present on planet Earth. Water quality changes may have an effect on the distribution and life cycle of aquatic organisms (Sharma et al., 2023; Slathia et al., 2023). Freshwater ecosystems are now among the most globally sensitive habitats due to the cumulative escalation in anthropogenic activities (Chandel et al., 2024; Choudhary et al., 2023; Albert et al., 2021; Sharma et al., 2018). When a number of water quality indicators are studied, it can be problematic to understand the results, especially when different anthropogenic stressors have an impact on the exact parameters and can mimic water quality across different categories (Brar et al., 2023; Hassan, 2020). The distribution and abundance of phytoplankton is severely impacted by the changes and instability in freshwater ecosystems. The distribution, quantity, richness, and makeup of the freshwater community are all directly influenced by cyclical variations in water quality (Sharma et al., 2024; Kumari et al., 2023; Majhi et al., 2023).

The water quality characteristics and phytoplankton of bodies of freshwater are linked and impacted by the variation in land use (Sharma et al., 2019; Singh et al., 2013). According to Malik et al. (2020a, b), nutrient dynamics also significantly influence the diversity of phytoplankton species. Damaging techniques for sand mining, dam building, and barrage construction have been shown to potentially affect aquatic ecosystems and pose a serious threat (Sharma et al., 2024; Sharma et al., 2018).

This study's goal was to assess the status of the water quality and phytoplankton diversity of the Ravi River using diverse environmental techniques to evaluate how anthropogenic activities, the building of dams and barrages, and other developments affected the quality of water and its ability to nurture freshwater organisms. Monitoring the water quality and gathering information about phytoplankton biology indices that may be used as bioindicators of the condition and contamination of the Ravi River had not been conducted until now. This study will give the baseline information regarding water quality in relation to phytoplankton diversity of the upper Ravi River basin.

MATERIAL AND METHODS

Background

The Ravi River flows through two states (Himachal Pradesh and Punjab) and one union territory of India (Jammu and Kashmir). The Ravi River originates in Himachal Pradesh, in the Bara Bhangal District of Kangra. There are four major tributaries of the Ravi River in Himachal Pradesh, namely Budhil, Baira, Siul, and Sewa rivers (Sharma, 2019). It flows for about 180 kilometers in Himachal Pradesh before entering Punjab, where it runs another 720 kilometers before draining a catchment of 14,441 km^2 in India. It forms a triangle with the Pir Panjal and Dhauladhar hills on either side as it flows westward. Four sampling zones were selected based on different geomorphology along the catchment area of the upper Ravi River in Himachal Pradesh (Tab. 1; Fig. 1).

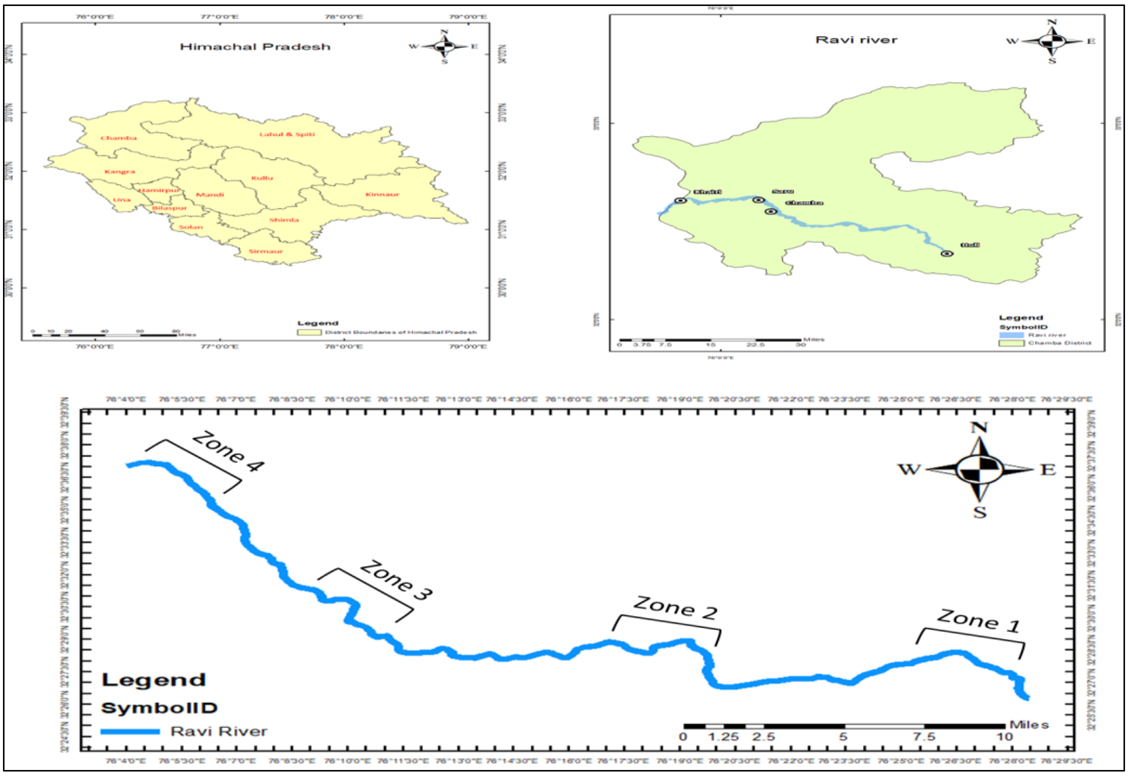

Figure 1: ArcGIS map showing selected study zones.

Table 1: Sampling zones along with their respective Geocoordinates

Sampling Zone	Name	Geo-Coordinates		Altitude	Reason for site selection
		Longitude	Latitude		
Zone 1	Holi	76.5503°E	32.3307°N	1,810 m	Having negligible anthropogenic impact
Zone 2	Chamba	76.1258°E	32.5534°N	1,006 m	Having considerable anthropogenic impact
Zone 3	Saru	76.0813°E	32.6038°N	489 m	River bed mining area
Zone 4	Khairi	75.9100°E	32.6066°N	475 m	Final zone after which river enters J&K UT.

Samples collection

Monthly sampling was conducted in selected zones of the study area from September 2022 to August 2023. Every month, the sampling procedure occurred over two days, with sampling from two different locations conducted simultaneously on one of these days. Sampling took place from six to nine o'clock in the morning. Materials used included bottles for sampling, pipettes, reagents, glassware, thermometers, pH meters, plankton nets, buckets, forceps, formaldehyde, and containers (Tab. 2). Some of the physicochemical characteristics that influence water quality were analyzed by using standard practical methodologies (Sharma et al., 2022; APHA, 2012; Goel and Trivedi, 1984)

Phytoplankton collection, identification and statistical analysis

One hundred liters of sampled water were filtered through a plankton net, and five percent formalin was applied to these samples that were obtained. After allowing the samples to settle for a twenty-four hours period, one millimeter of concentrated solution was moved across the glass slide both horizontally and vertically for counting. Additional concentration was added to the Sedgwick Rafter counting cell after the sample was introduced.

Slides were prepared using the concentrated sample. These slides were examined using a digital microscope, and identification was carried out. Phytoplankton was identified according to Needham and Needham (1962).

Canonical Correspondence Analysis (CCA) was performed using Paleontological Statistics (PAST, Version 4.03) software to determine the relationship between dominant phytoplankton species and water quality parameters.

Diversity indices

A quantitative metric that shows the number of distinct types (such as species) present in a dataset (a community) is referred to as a diversity index (Supriatna, 2018). The calculation of diversity indices is crucial in determining the health of aquatic ecosystems. These indices assist in the evaluation of water quality through the precise depiction of variations in phytoplankton structure and nutrient concentrations (Cai et al., 2022).

Shannon Index

$$\text{Shannon Index (H)} = -\sum_{i=1}^{s} p_i \, 1n \, p_i$$

In this formula, p represents the comparison between the number of individuals of a certain species found (n) and the overall number of individuals found (N). The natural log, denoted as ln, represents the sum of the calculations, and the number of species, denoted as s, represents the total number of individuals found.

Table 2: Instruments used, methodology, and studied parameters.

Station number	Parameter	Instrument	Method
1.	Water temperature (°C)	Digital thermometer (Digital TP101).	The physicochemical characteristics that influence water quality were analyzed by using standard methodologies (APHA, 2012) and (Goel and Trivedi, 1984)
2.	pH	pH meter (eco Testr)	
3.	Total dissolved solids (mg/L)	TDS meter (eco Testr)	
4.	Conductivity ($\mu S/cm^2$)	Conductivity meter (Cyber Scan PCD 650)	
5.	Dissolved oxygen (mg/L)	DO kit (Cyber Scan PCD 650)	
6.	Biological oxygen demand (mg/L)	Winkler's method	
7.	Turbidity (NTU)	Tube method	
8.	Nitrate (mg/L)	Spectrophotometry	
9.	Phosphorous	Spectrophotometry	
10.	Sulphate	Turbidimetric method	
11.	Calcium, and magnesium	Titration method/Flame photometry	
12.	Phytoplankton analysis	Plankton net, Sedgwick rafter scale and digital microscope (Magnus CH20iLED) with camera (Magnus Magcam DC Plus 10)	Phytoplankton were identified according to Needham and Needham (1962)
13.	Statistical analysis	Using computer software correlation between water quality parameters and phytoplankton was calculated	Canonical Correspondence Analysis (CCA) was performed using Paleontological Statistics (PAST, Version 4.03) Software

Simpson Index

$$\text{Simpson Index (D)} = \frac{1}{\sum_{i=1}^{s} p_i^2}$$

The Simpson index, denoted as D, represents the proportion of individuals belonging to a specific species that were discovered (n/N) divided by the overall number of individuals discovered (N). Additionally, Σ represents the sum of the calculations, and s represents the total number of species present.

Evenness Index

$$\text{Species Eveness Index} = \frac{\text{SDI}}{\max(\text{SDI})} = -\sum_{i}^{m}(p_i \ * 1n(p_i\ ))/1n(m)$$

In order to offer information on the composition and richness of an area, the Species Evenness Index (SEI) should be used. The number of distinct land cover types (m) recorded along the straight line, as well as the relative abundances of those land cover types (Pi), are considered in this calculation. To determine it, the Shannon diversity index is divided by its maximum value, denoted by the symbol h (m). This means that it can range anywhere from 0 to 1, and it is not overly complicated to understand.

RESULTS AND DISCUSSION

Physiochemical parameters

The evaluation of the water quality, as well as the restoration of habitat ecology, is significantly aided by the regular monitoring of physicochemical water quality parameters (Sharma et al., 2022; Rahman et al., 2021). The outcomes of the physical and chemical indicators that were measured at the chosen sampling sites in Ravi River are as follows.

The mean variation in water temperature ranged from 14.6°C in zone 1 to 16.5°C in zone 3 (Fig. 2). A similar trend of water temperature was observed in the Beas River in Himachal Pradesh (Kumar et al., 2015).

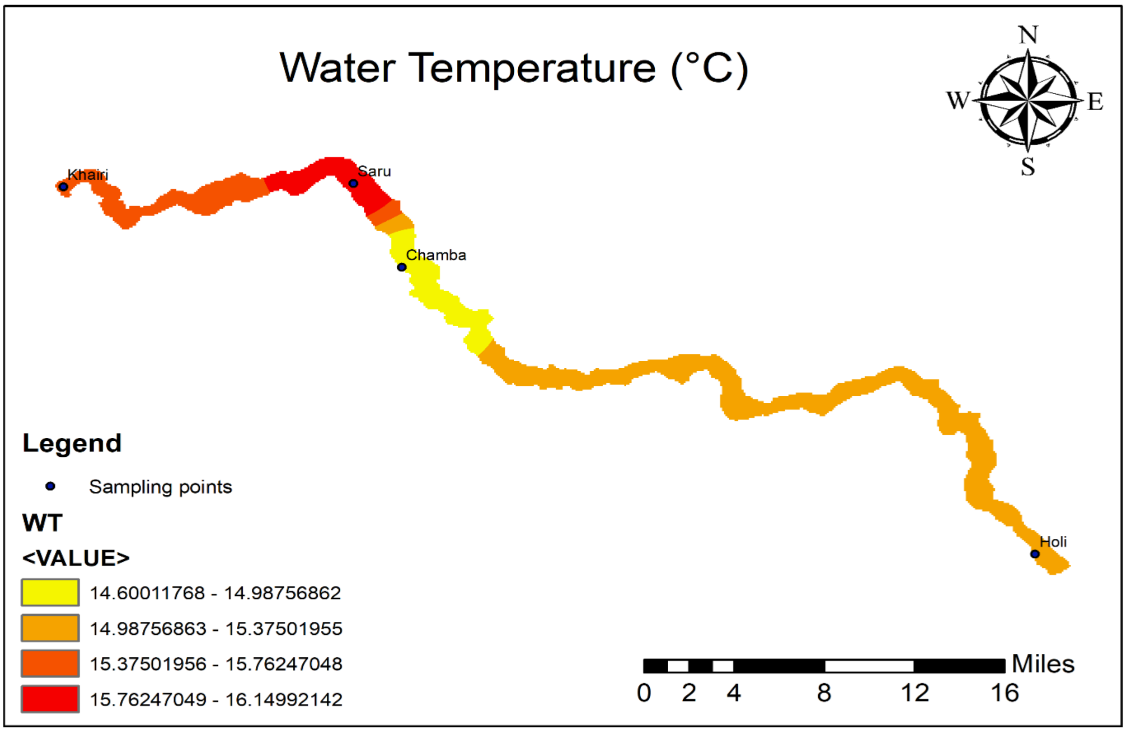

Figure 2: Mean variation of water temperature in selected sampling zones of river Ravi.

In this research, the mean value in total dissolved solids (TDS) ranged between 129.57 mg/L in zone 1 to 133.68 mg/L in zone 3 (Fig. 3). These values are within the permissible limit in all four studied zones. TDS values were within a similar range in the Ganga River (Malik et al., 2021). Lower TDS in Ravi River might be attributed to lower BOD, less silt, and reduced nutrient concentration. Only magnesium was present in higher amounts.

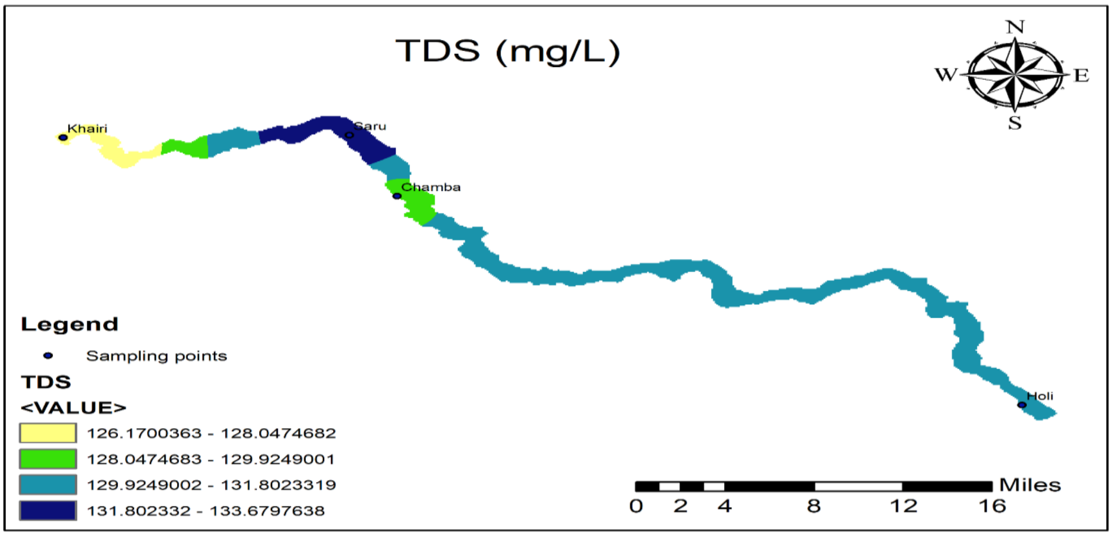

Figure 3: Mean variation of TDS
in selected sampling zones of river Ravi.

Together with the rise in TDS up to a certain level, there is an increase in biomass, growth rate, phytoplankton count, and chlorophyll-a (Chapman and McPherson, 2016).

The mean values of electrical conductivity (EC) ranged from 207.31 μmhos/cm^2 to 213.88 μS/cm^2. Electrical conductivity was found to be 217.83 ± 137.56 μS/cm^2 in the Beas River (Sharma et al., 2018; Sharma and Kumar, 2016). TDS = k EC (in 25°C) is a basic equation that typically shows the relation between these two variables. The pH readings in the upper Ravi River were within the permissible range, which is between 6.5 and 8.5, and varied from 7.33 to 7.63. In the third sampling zone, the pH was measured and found to have the lowest mean, a value of 7.33 (Fig. 4). The alkaline quality of the water in the lower reaches of the Ravi River has also been documented by Mahmood et al. (2000) in Pakistan and by Kumar and Dua (2010) in Madhopur (Punjab, India).

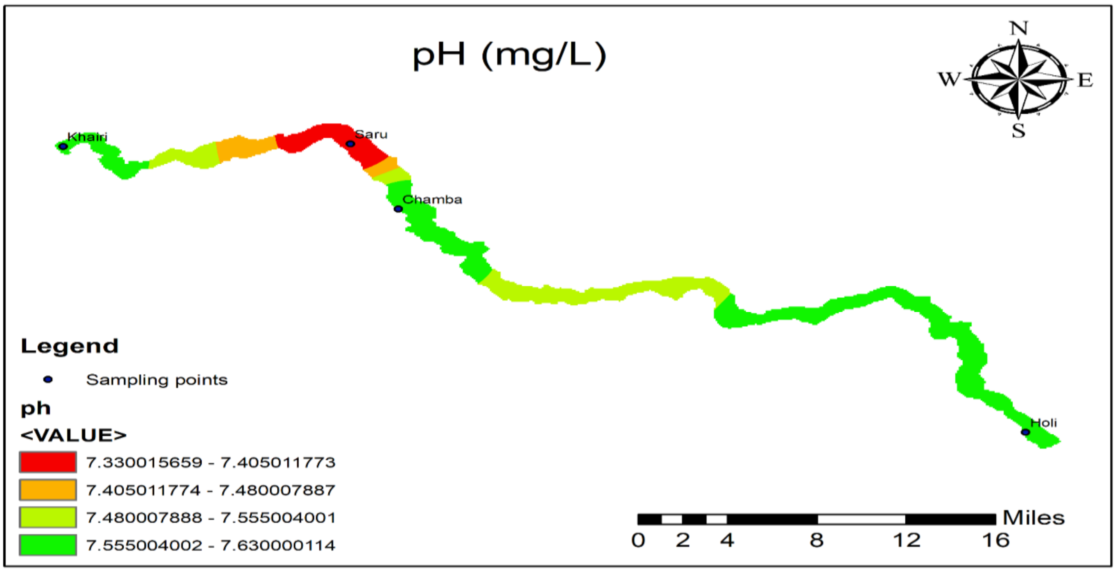

Figure 4: Mean variation of pH
in selected sampling zones of river Ravi.

Turbidity ranged between 60.5 NTU and 200.0 NTU over the course of the current investigation, with the highest turbidity reported in zone 3 (Fig. 5). All of the sampling zones experienced turbidity levels exceeding the standard limit of 5 NTU, as per FMEnv (2011). The highest turbidity values were observed during the monsoon season. Similarly, Kamboj et al. (2020) reported a similar trend in the Ganga. Tyler et al. (2022) found that excessive turbidity directly impacts organisms living in aquatic environments. However, levels of turbidity in rivers do not significantly affect plankton populations, particularly when the turbidity results from natural sources, such as particle resuspension from riverbeds or changes in water flow (Neun et al., 2022).

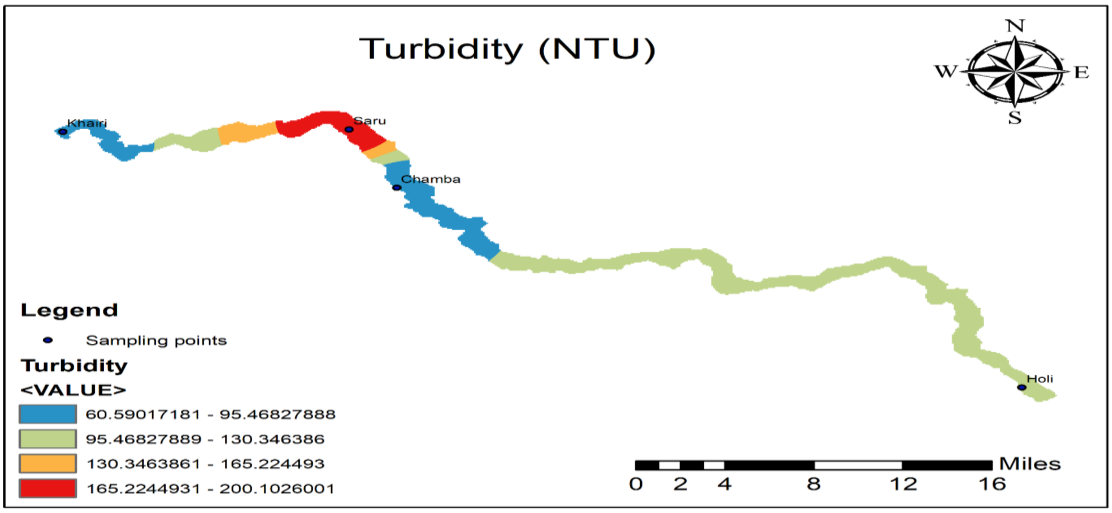

Figure 5: Mean variation of turbidity
in selected sampling zones of river Ravi.

Sharma et al. (2019) revealed that a dissolved oxygen (DO) content of more than 5 mg/L is essential for maintaining the freshwater ecosystem, supporting a diverse aquatic community, and enhancing fish production. According to Hanjaniamin et al. (2023), DO stratification can occur when turbidity levels are higher. In the selected sampling zones of river Ravi, the DO ranged from 7.27 to 8.13 mg/L (Fig. 6).

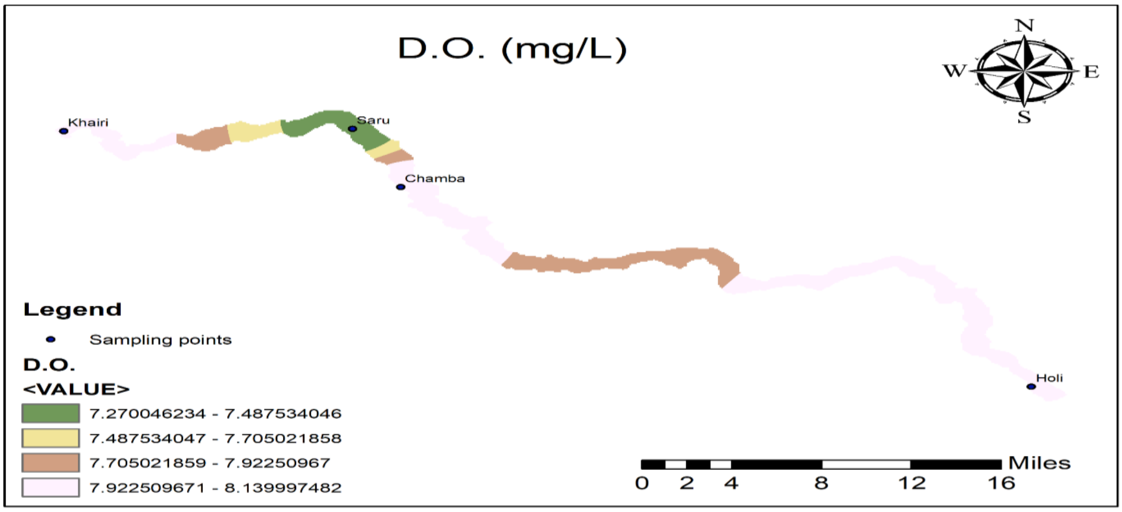

Figure 6: Mean variation of DO
in selected sampling zones of river Ravi.

All mean DO values were within the permissible limit set by FMEnv. (2011), which is greater than 5 mg/L. The concentration of dissolved oxygen in river water is influenced not only by natural areation but also by photosynthetic activity from phytoplankton and water temperature (Ni'am et al., 2022). On the other hand, the biological oxygen demand (BOD) ranged from 1.50 to 2.01 mg/L, below the acceptable limit of 3 mg/L. Sampling zone 3 had higher BOD levels compared to zones 1, 2, and 4 (Fig. 7). BOD is an indicator of organic pollutants in the river (Giri et al., 2022). Lower BOD levels suggest fewer organic pollutants and better water quality, indicating less contamination from sources such as domestic, agricultural, and commercial waste (Chapra et al., 2021). Meanwhile, the mean value of free carbon dioxide (FCO_2) was 2.36 mg/L in zone 1 and 2.58 mg/L in zones 3 and 4. A similar trend was observed in the Ganga River by Kamboj et al. (2020).

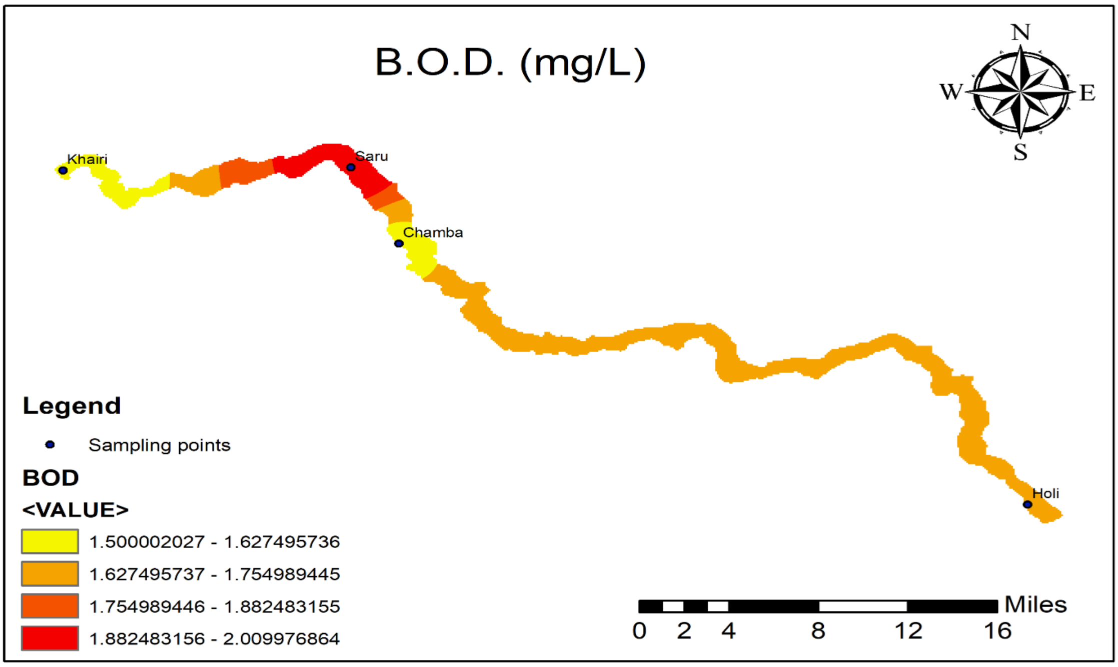

Figure 7: Mean variation of BOD
in selected sampling zones of river Ravi.

Calcium levels were within permissible limits in all sampling zones, ranging from 12.19 mg/L to 20.18 mg/L with sampling zone 3 having substantially higher levels than the others (Fig. 8). Magnesium levels at all sampling stations were also adequate, with mean magnesium levels ranging from 52.5 mg/L in zone 1 to 71 mg/L in zone 3 (Fig. 9). In the Jehlum River, calcium and magnesium values ranging from 23-45 mg/L and 4-22 mg/L were reported by Mir et al. (2016). Possible sources of calcium and magnesium in river water include geological formations, soil types, vegetation, local environmental conditions, and anthropogenic factors such as agricultural and municipal effluent (Katutis and Rudzianskaitė, 2015).

The existence, growth, and survival of phytoplankton depend on calcium and magnesium. Magnesium is necessary for chlorophyll synthesis, which enables effective photosynthesis and the creation of organic material that support marine environments, and calcium helps to maintain the rigidity of their cell walls (Ahmed et al., 2023; Kumar et al., 2019).

Phosphorous concentrations varied from 0.12 mg/L in sampling zone 1 to 0.44 mg/L in sampling zone 3 (Fig. 10), with the maximum value still within the permissible limit. Various amounts of phosphorous serve as an indicator of nutrient concentrations and eutrophication in the freshwater ecosystem (Akinnawo, 2023; Kamboj and Kamboj, 2020; Kumar et al., 2018). Phosphorus is essential for phytoplankton as it is a key component in nucleic acids, phospholipids, and adenosine triphosphate (ATP), which are vital for cellular functions such as growth and reproduction. Excessive phosphorus can lead to eutrophication, a phenomenon where excessive growth of algae reduces oxygen levels in water, resulting in detrimental effects on aquatic ecosystems (Lovio-Fragoso et al., 2021; Kumar et al., 2018). Mean sulphate concentrations were well within the permissible limits in the River Ravi, ranging from 0.2 mg/L in zones 1 to 0.49 mg/L in zone 3 (Fig. 11).

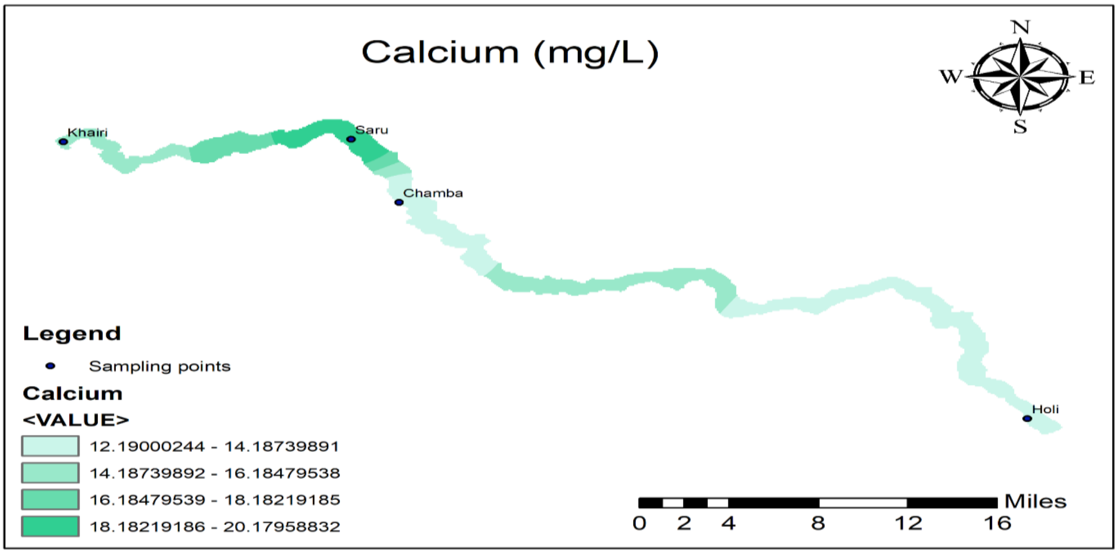

Figure 8: Mean variation of calcium
in selected sampling zones of river Ravi.

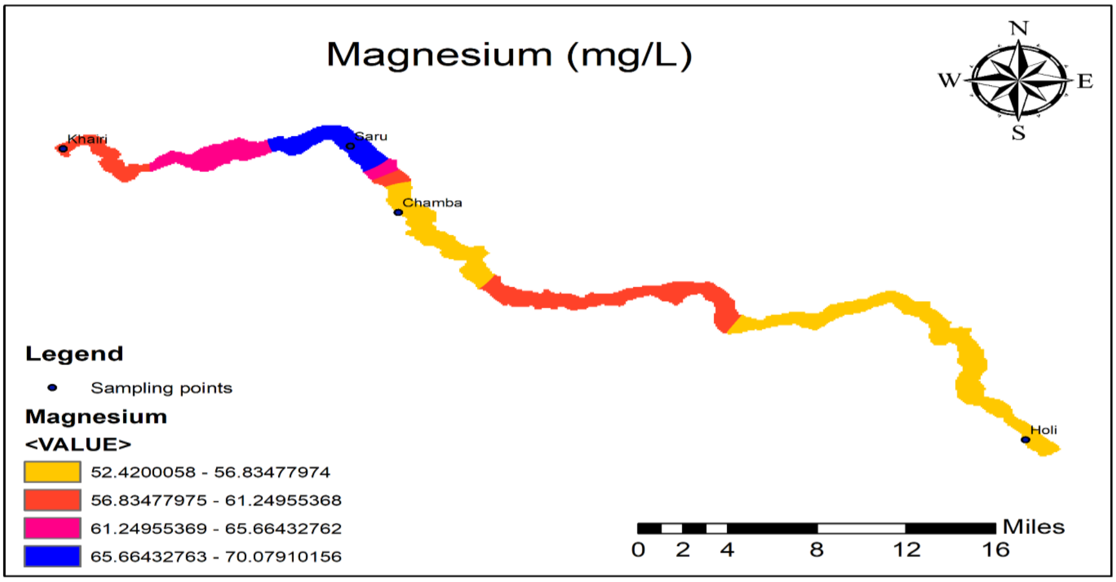

Figure 9: Mean variation of magnesium
in selected sampling zones of river Ravi.

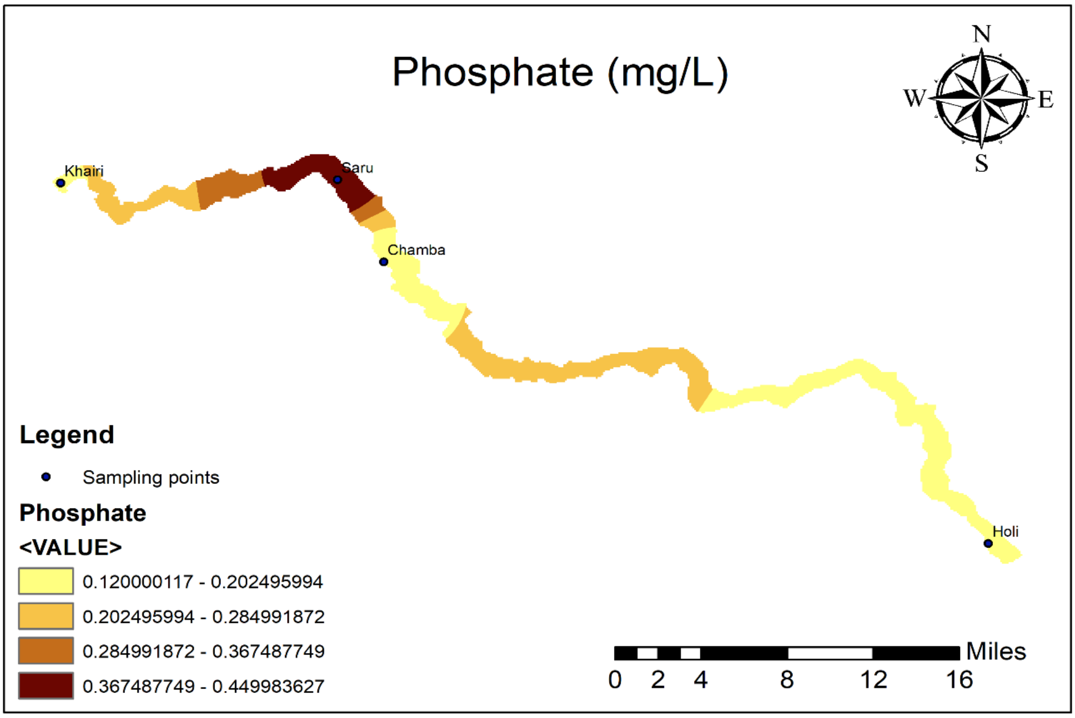

Figure 10: Mean variation of phosphorus
in selected sampling zones of river Ravi.

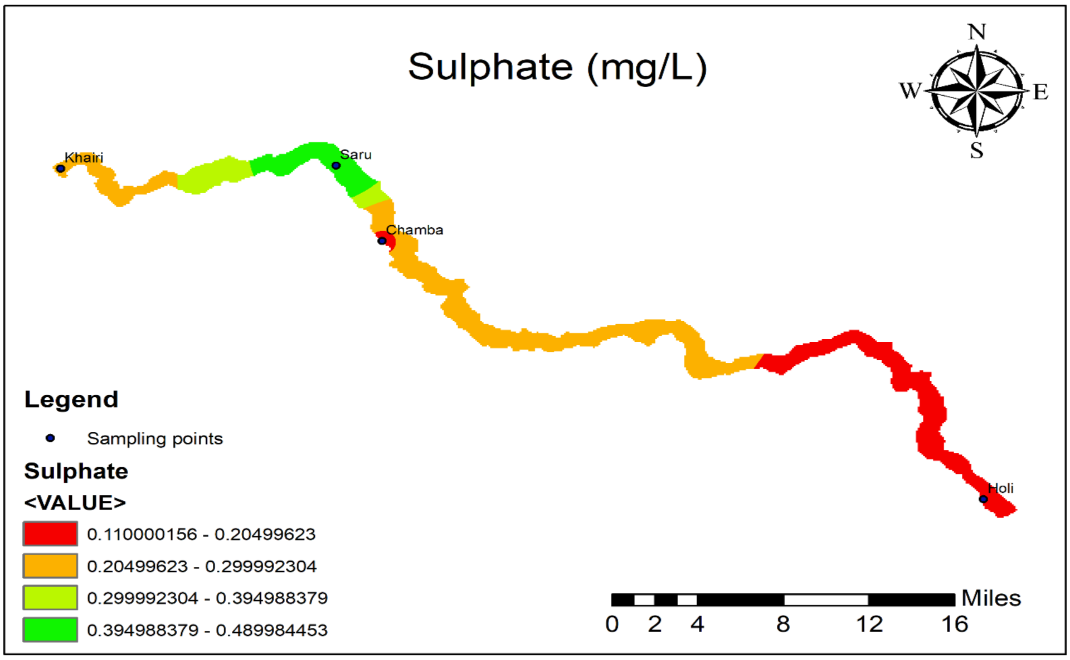

Figure 11: Mean variation of sulfur
in selected sampling zones of river Ravi.

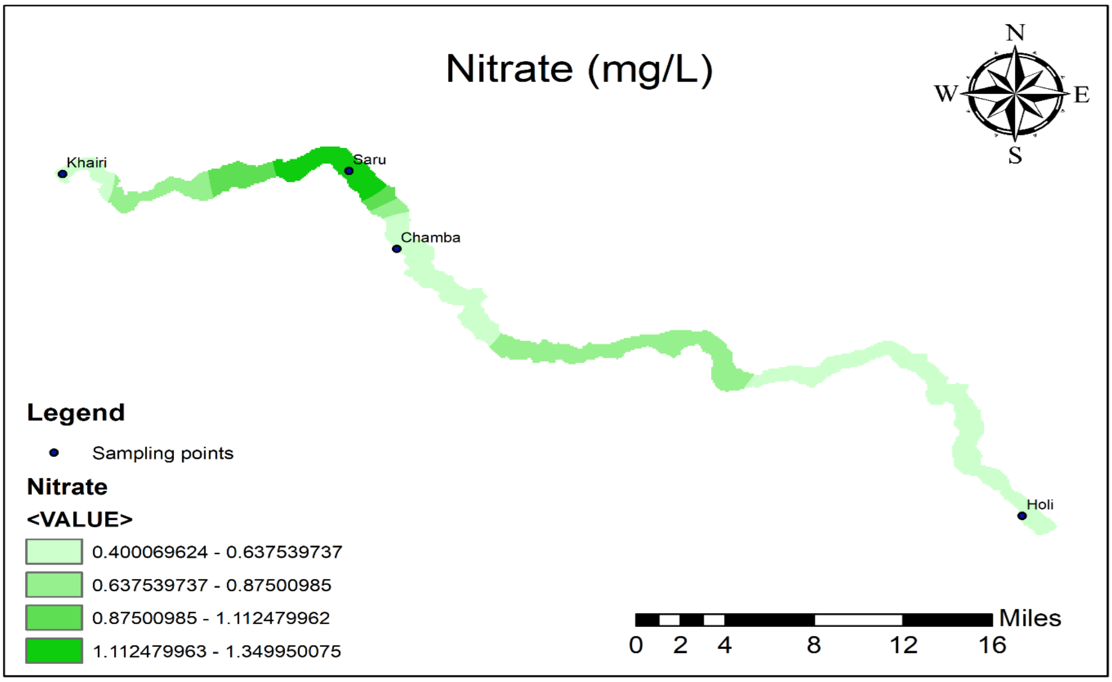

Figure 12: Mean variation of nitrate
in selected sampling zones of river Ravi.

Sampling zone 3, exhibited significantly higher levels compared to the other sampling stations. Although the investigation found low ionic concentrations, they remained within acceptable limits. The low ionic levels might be attributed to the region's geomorphology and rock composition, a trend similarly observed in the Bhagirathi River (Sharma et al., 2020). Nitrates have a vital role in promoting phytoplankton growth by serving as a primary source of nutrients. They significantly ifluence the metabolism and enzyme activity of phytoplankton, particularly nitrate reductase, which is essential for their survival and the production of blooms (Kumar et al., 2023; Rahav et al., 2020). Additionally, nutrients like nitrogen and phosphorus are vital for supporting plankton growth, especially during the winter season (Damseth et al., 2024; Malik et al. 2018; Thakur et al. 2013).

Biotic parameters

Phytoplankton generate sugars by utilising sunlight, carbon dioxide, and the nutrients from water, which fuel the food web in estuaries ecosystems. The abundance of growing phytoplankton is crucial as they serve as a source of nutrition for aquatic organisms such as zooplankton and fish (Parker and Lehman, 2021). Phytoplankton, due to their short life span and sensitivity to changing water quality, serve as an indicator of water quality (Dembowska, 2021), particularly in river ecosystems. In the Ravi River in Himachal Pradesh, the phytoplankton community is comprised of five main groups: Xanthophyceae, Euglenophyceae, Myxophyceae, Chlorophyceae, and Bacillariophyceae. A total of 23 phytoplankton genera were recorded across different zones during the research (Fig. 17). Bacillariophyceae (Fig. 13) was the most dominant in all sampling zones, followed by Chlorophyceae (Fig. 14), Myxophyceae (Fig. 15), Euglenophyceae (Fig. 16), and Xanthophyceae, which was the least dominant group.

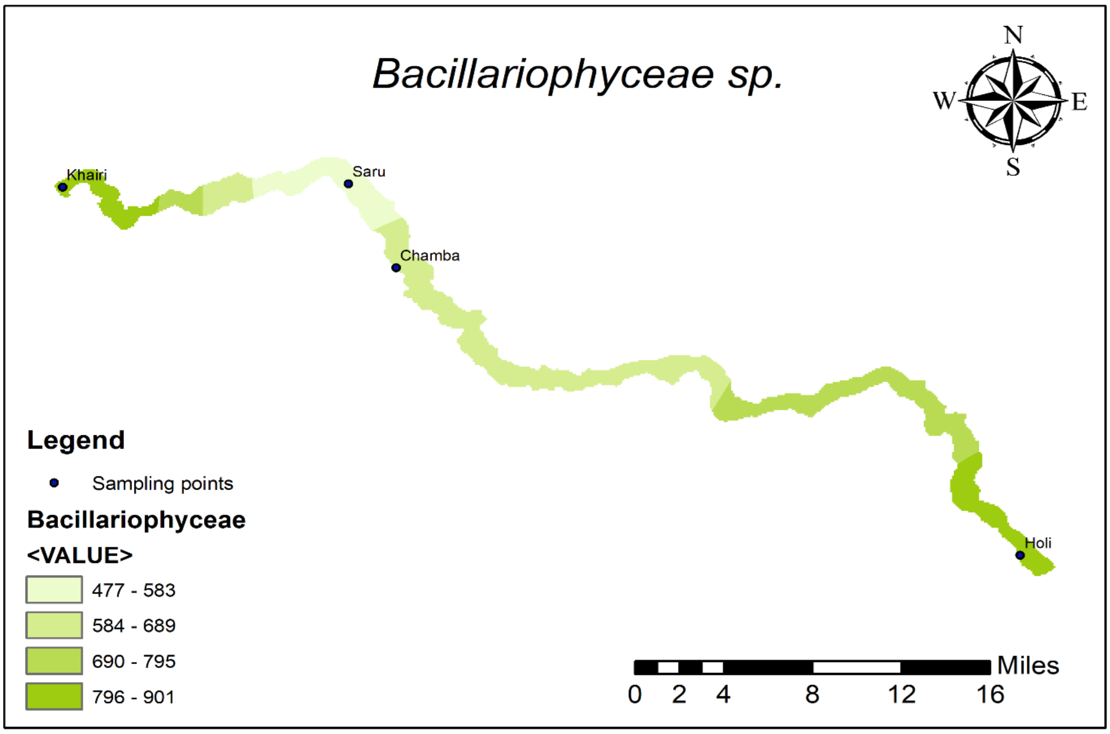

Figure 13: Mean variation of Bacillariophyceae in selected sampling zones of river Ravi.

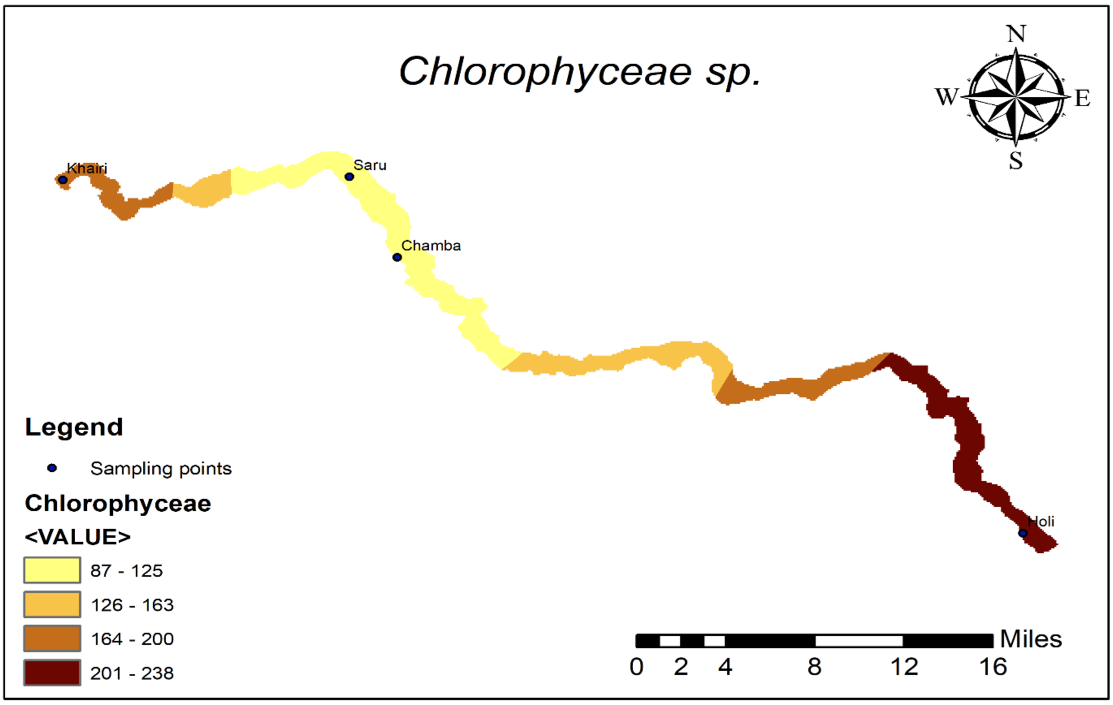

Figure 14: Mean variation of Chlorophyceae in selected sampling zones of river Ravi.

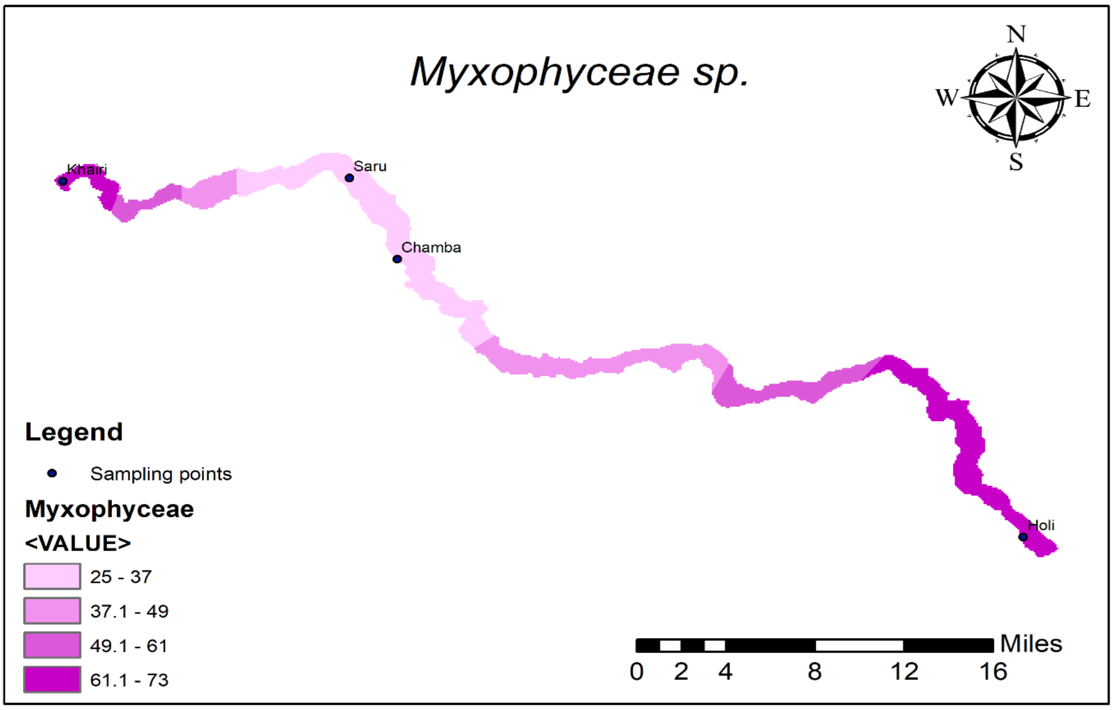

Figure 15: Mean variation of Myxophyceae
in selected sampling zones of river Ravi.

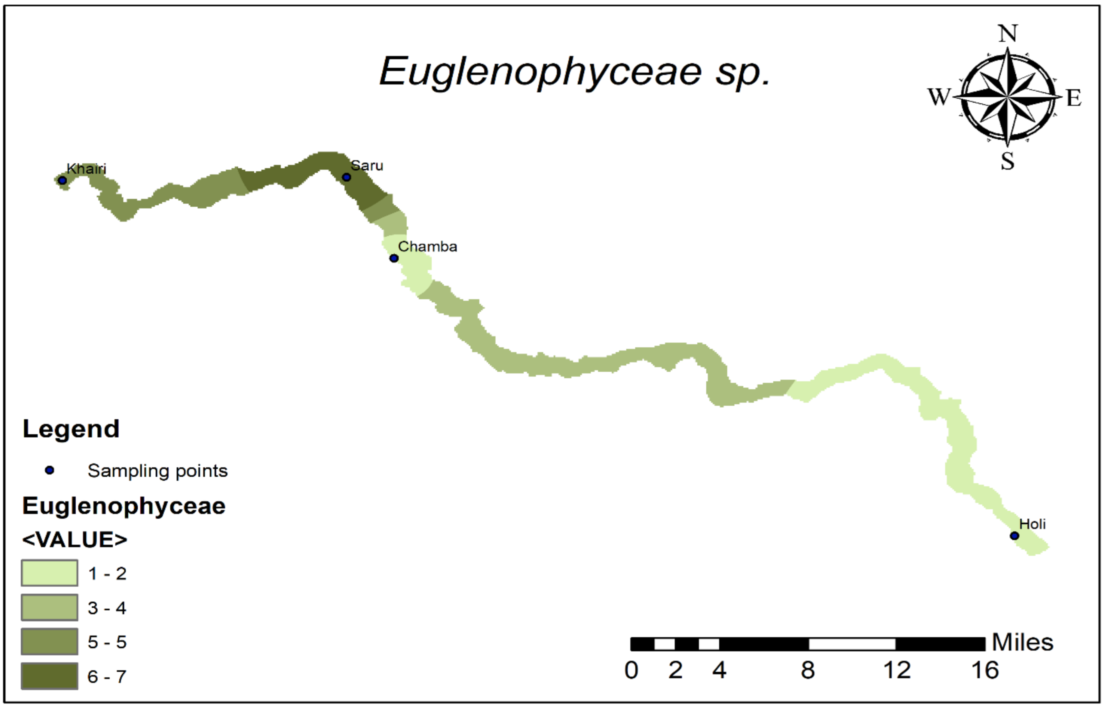

Figure 16: Mean variation of Euglenophyceae
in selected sampling zones of river Ravi.

Sampling zone 4 recorded the highest number of phytoplankton, while sampling zone 3 witnessed the least number of phytoplankton individuals.

This pattern of phytoplankton abundance may be attributed to the physicochemical characteristics of the water and various developmental activities taking place along the Ravi River basin. Factors such as the presence of a dam downstream of zone 1 and zone 3, along with temporary riverbed mining in zone 3, likely influence the distribution of phytoplankton. Sand mining in zone 3 has lead to the degradation of both the physical and chemical characteristics of the riverbed. This results in water quality and habitat ecology, and reduces the presence of appropriate surfaces for plankton to adhere to, affecting their growth. Additionally, increased turbidity, caused by these activities, reduced light penetration, limiting photosynthetic activity and primary productivity, despite the presence of nutrients (magnesium, nitrates, etc.) that are vital for phytoplankton.

A similar trend was observed by Kumar et al. (2018) in the Beas River and by Malik et al. (2021) in the Ganga River. Among all the phytoplankton genera in the upper stretch of Ravi River, *Achananthes* sp. was the most abundant.

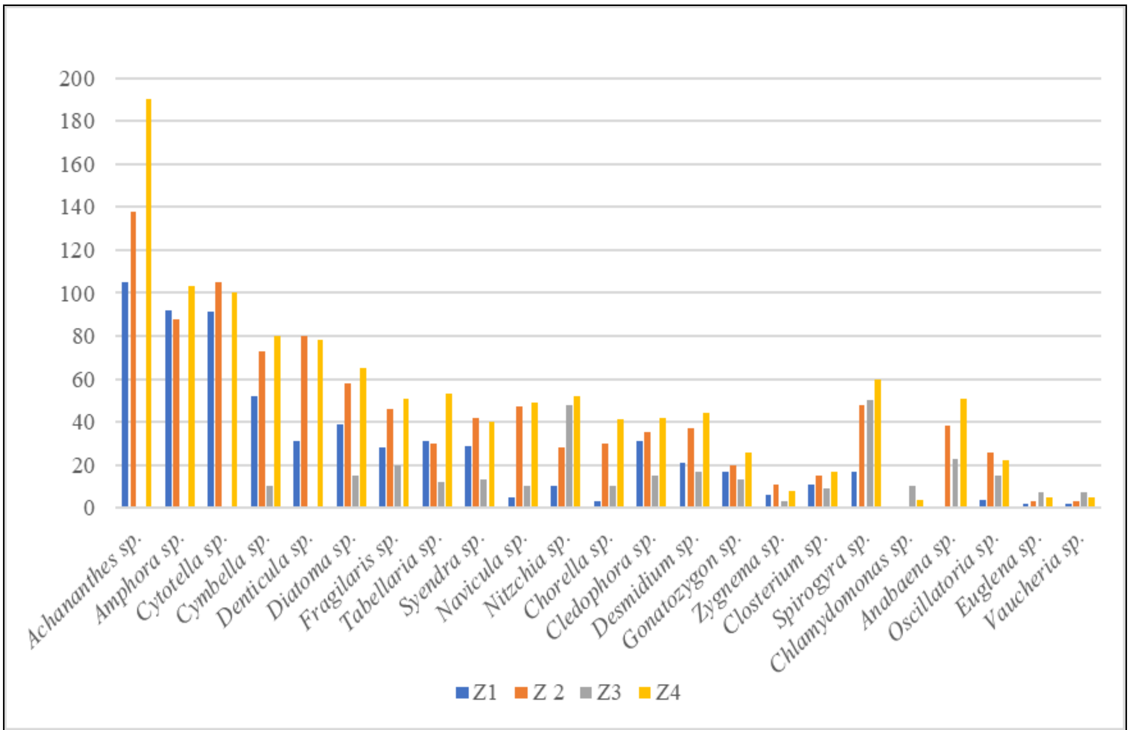

Figure 17: Phytoplankton assemblage in Ravi River
(Z1 = Zone 1, Z2 = Zone 2 Z3 = Zone 3 and Z4 = Zone 4).

However, species like *Chlamydomonas* sp., *Euglena* sp., and *Vaucheria* sp. were dominant in zone 3 (Fig. 17). A similar trend for *Achananthes* sp. was observed by Srivastava et al. (2020) in the Ganga River in the Gangotri region, where they concluded that the river water quality was affected by dam construction, altering the phytoplankton assemblage. Additionally, municipal dumping and anthropogenic activities in zone 2 also impacted water quality and plankton distribution. Kaur and Singh (2017) similarly reported that household water and dumping can influence plankton diversity and abundance in certain river areas.

The Shannon index was highest in zone 4, with a maximum of 2.795, indicating that this zone exhibits the greatest species diversity and a more even distribution of individuals compared to other zones. The other zones followed closely, with values of 2.776 in zone 2, 2.771 in zone 3, and 2.642 in zone 1. A higher Shannon index value indicates higher diversity. Conversely, the Simpson index was at 0.921 in zone 2 and lowest at 0.899 in zone 1. Values of the Simpson index ranges from 0 to 1, where lower diversity is indicated by values close to 0 and higher diversity is indicated by values close to 1. The maximum evenness value of 0.729 was reported in zone 2, while the minimum value 0.694 was recorded in zone 3. These results suggest that the species in zone 2 are more evenly distributed compared to the other zones (Tab. 4). An eveness value closer to 1 indicates the highest eveness. For the Shannon index, the highest value of 3.14 and lowest value of 3.07 was observed by Malik et al. (2021), with a similar trend reported by Dembowska (2021).

The phytoplankton assemblage structure and diversity indices reveal that zone 3 has a lower number and more uneven distribution compared to other zones. This discrepency may be attributed to riverbed mining and various anthropogenic activities in the area. Additionally, several sensitive genera are notably absent in zone 3. On the contrary, the lower diversity indices in zone 1 can be attributed to the absence or negligible numbers of certain pollution-resistant phytoplankton genera. The high altitude, steeper slope and high water velocity in zone 1 may also contribute to the reduced presence or abundance of certain species.

Table 4: Mean variation in diversity indices of phytopankton's in selected study sites.

	Zone 1	Zone 2	Zone 3	Zone 4
Shannon_H	2.642	2.776	2.771	2.795
Simpson_1-D	0.8997	0.921	0.9173	0.9196
Evenness_e^H/S	0.7019	0.7296	0.6944	0.7111

The technique used to explore the connections between biological groups of species and their environmental contexts is Canonical Correspondence Analysis (CCA) (Zhou et al., 2023). The results of CCA analysis were plotted using two axis (Figs. 19-22). The length of a variable's vector in CCA reflects the significance of that variable. In our analysis, the longest vector length was associated with dissolved oxygen, indicating a significant relationship across all zones. Conversely, the vector lengths of water temperature and BOD were oriented in opposite direction of dissolved oxygen in all the zones, indicating an inverse relationship between these water quality parameters. According to Kamboj et al. (2022), increased water temperature tends to decrease the level of dissolved oxygen in water. Moreover, a moderate increase in light intensity and water temperature enhances phytoplankton growth (primary productivity) resulting in higher BOD (Malik et al., 2020a).

In zone 1, species showed a significant positive relation with phosphorous, while in zone 2, species had a positive relationship with magnesium. In zone 3, a statistically significant positive relation was found between BOD and *Chlamydomonas* sp. (Figs. 19-21). Zone 3 also exhibited the longest vector lengths, most nutrient parameters, water temperature, turbidity, and BOD. All zones showed a significant positive relation in June and July for these parameters, indicating a disturbance in the water quality and plankton community in zone 3. According to Malik et al. (2020b), sediment load and water temperature of the riverine system increases during the rainy season due to landslides and surround run off, leading to higher turbidity.

The highest number of phytoplankton was observed in zone 4, followed by zone 2, zone 1 and zone 3 respectively. The eigenvalue of axis 1 accounted for 28.47%, 31.34%, 29.43%, and 29.29% of the relationship between environmental variables and phytoplankton diversity in zones 1, 2, 3, and 4, respectively. The corresponding eigenvalues were 0.01298, 0.013703, 0.013425, and 0.014039. Meanwhile, axis 2, with eigenvalues of 0.010467, 0.01069, 0.011228, and 0.010478 explained 22.95%, 24.45%, 24.61%, and 21.86% of the relationship between environmental factors and phytoplankton diversity in the respective zones (Tab. 5). These results clearly demonstrate the inverse relationship between turbidity and key physiochemical parameters essential for sustaining plankton communities.

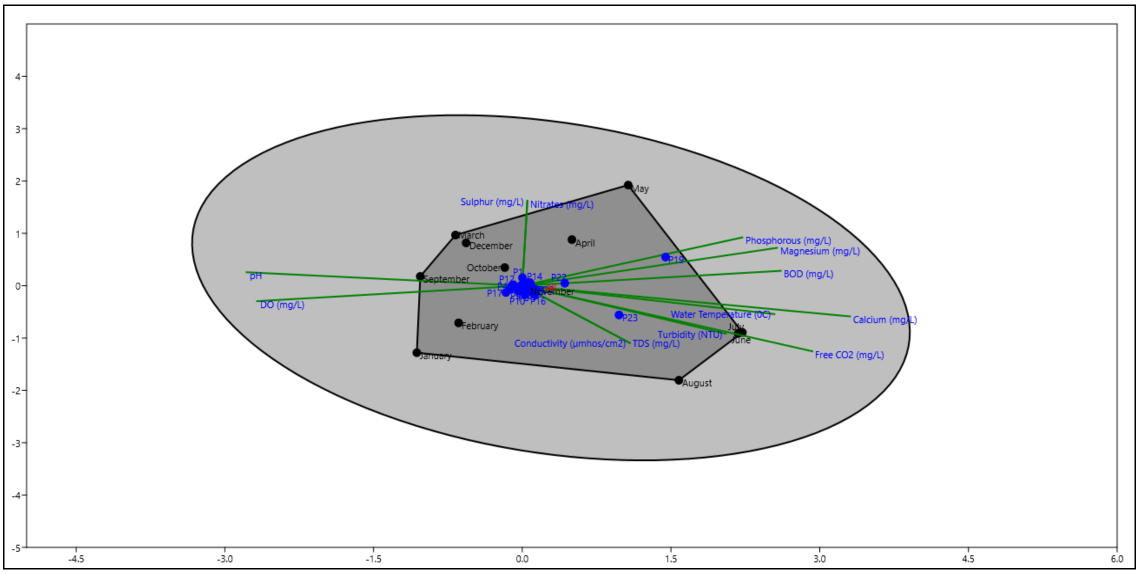

Figure 18: Ecological factors and phytoplankton taxa in a CCA biplot of sampling zone 1.

Table 5: Biplot of Canonical Correspondence Analysis (CCA) displaying the relationship between environmental parameters and phytoplankton genera.

	Zone 1		Zone 2		Zone 3		Zone 4	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
P1	0.001	0.153	0.008	0.163	0.027	0.135	0.031	0.047
P2	–0.039	–0.098	–0.028	–0.082	–0.043	–0.130	–0.075	0.086
P3	–0.061	–0.029	–0.053	–0.013	–0.060	–0.031	–0.067	0.028
P4	–0.109	–0.006	–0.125	–0.008	–0.126	0.048	–0.101	–0.112
P5	0.043	–0.076	0.054	–0.063	0.034	–0.087	0.026	0.035
P6	–0.001	0.012	–0.023	–0.024	–0.026	0.057	0.014	–0.148
P7	0.085	0.017	0.094	0.044	0.101	–0.035	0.064	0.155
P8	–0.004	–0.065	–0.007	–0.026	0.001	–0.101	–0.058	0.147
P9	–0.121	–0.066	–0.120	–0.076	–0.143	–0.109	–0.158	0.041

Table 5 (continued): Biplot of Canonical Correspondence Analysis (CCA) displaying the relationship between environmental parameters and phytoplankton genera.

	Zone 1		Zone 2		Zone 3		Zone 4	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
P10	0.025	–0.166	0.019	–0.144	0.008	–0.186	–0.041	0.084
P11	0.036	–0.032	0.026	–0.062	0.018	0.010	0.053	–0.125
P12	–0.090	0.018	–0.107	–0.026	–0.111	0.069	–0.060	–0.174
P13	–0.008	0.012	–0.001	–0.028	0.003	0.061	0.052	–0.143
P14	0.061	0.060	0.048	0.027	0.064	0.105	0.099	–0.135
P15	0.065	0.015	0.046	–0.010	0.067	0.035	0.071	–0.064
P16	0.124	–0.171	0.112	–0.217	0.106	–0.071	0.150	–0.233
P17	–0.165	–0.128	–0.132	–0.088	–0.143	–0.138	–0.178	0.100
P18	0.036	–0.032	0.026	–0.062	0.018	0.010	0.053	–0.125
P19	1.445	0.548	1.422	0.678	1.429	0.255	1.337	0.630
P20	0.127	–0.065	0.111	–0.099	0.117	–0.050	0.116	–0.071
P21	0.078	0.059	0.041	0.013	0.043	0.070	0.072	–0.114
P22	0.429	0.048	0.443	–0.042	0.458	0.057	0.505	–0.150
P23	0.975	–0.558	1.088	–0.510	0.960	–0.547	0.991	0.137
September	–1.029	0.178	–0.992	0.408	–1.010	–0.161	–1.183	0.944
October	–0.177	0.347	–0.243	0.107	–0.165	0.444	–0.066	–0.619
November	0.078	0.018	–0.026	–0.517	–0.070	0.585	0.384	–2.049
December	–0.566	0.818	–0.707	0.440	–0.600	1.439	–0.174	–1.973
January	–1.064	–1.280	–1.008	–1.106	–1.136	–1.268	–1.305	0.403
February	–0.643	–0.711	–0.569	–0.610	–0.665	–0.674	–0.717	0.155
March	–0.674	0.968	–0.578	1.124	–0.463	0.652	–0.555	0.780
April	0.500	0.881	0.575	1.012	0.650	0.625	0.617	0.660
May	1.068	1.923	0.988	2.015	1.180	1.422	1.096	0.796
June	2.176	–0.914	2.065	–0.812	1.985	–1.050	1.771	0.585
July	2.220	–0.893	2.237	–0.813	2.178	–0.866	2.066	0.365
August	1.579	–1.806	1.611	–1.779	1.453	–1.852	1.228	0.519
Water (°C)	0.727	–0.155	0.802	–0.120	0.763	–0.372	0.736	0.430
pH	–0.795	0.074	–0.812	0.205	–0.512	0.189	–0.490	–0.153
TDS (mg/L)	0.310	–0.313	0.309	–0.303	0.285	–0.332	0.251	0.141
Conductivity (μmhos/cm^2)	0.310	–0.313	0.309	–0.303	0.285	–0.332	0.251	0.141
Turbidity (NTU)	0.586	–0.262	0.482	–0.168	0.030	–0.294	0.267	0.318
DO (mg/L)	–0.764	–0.085	–0.709	–0.069	–0.724	0.048	–0.717	–0.188

Table 5 (continued): Biplot of Canonical Correspondence Analysis (CCA) displaying the relationship between environmental parameters and phytoplankton genera.

	Zone 1		Zone 2		Zone 3		Zone 4	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
BOD (mg/L)	0.745	0.081	0.586	0.165	0.639	0.148	0.789	0.377
Free CO2 (mg/L)	0.836	–0.358	0.839	–0.322	0.763	–0.432	0.720	0.255
Calcium (mg/L)	0.945	–0.168	0.727	0.293	0.771	–0.033	0.790	0.486
Magnesium (mg/L)	0.734	0.207	0.717	0.339	0.773	–0.010	0.790	0.540
Phosphorous (mg/L)	0.634	0.264	0.356	0.034	0.282	0.071	0.802	0.491
Sulphate (mg/L)	0.015	0.463	0.040	0.351	0.287	0.426	0.781	0.231
Nitrates (mg/L)	0.015	0.463	0.356	0.034	0.282	0.071	0.802	0.491
Eigenvalue	0.013	0.010	0.014	0.011	0.013	0.011	0.014	0.010
%	28.47	22.95	31.34	24.45	29.43	24.61	29.29	21.86

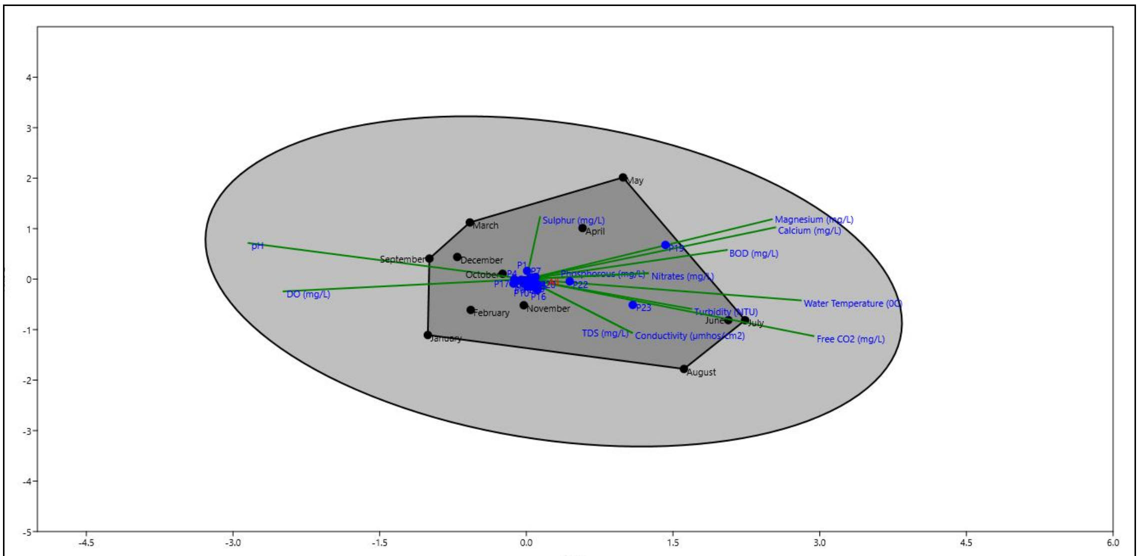

Figure 19: Ecological factors and phytoplankton taxa
in a CCA biplot of sampling zone 2.

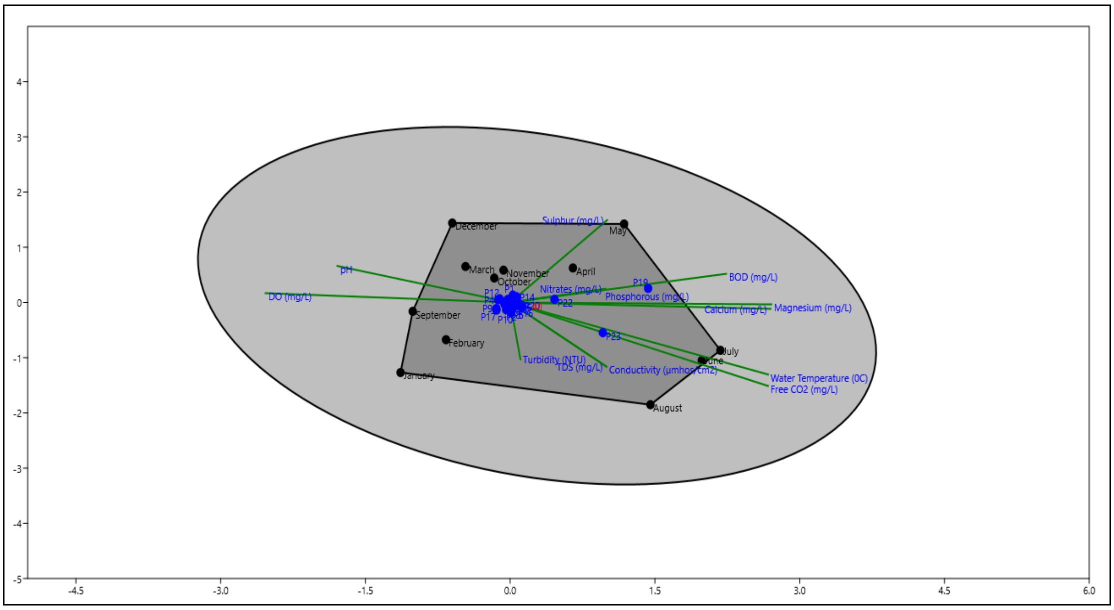

Figure 20: Ecological factors and phytoplankton taxa
in a CCA biplot of sampling zone 3.

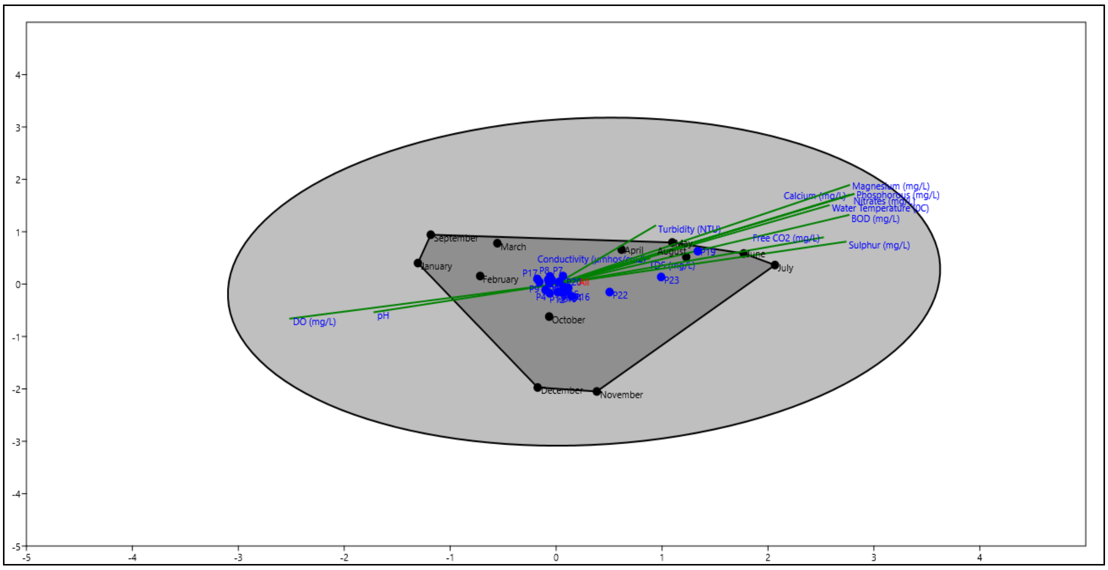

Figure 21: Ecological factors and phytoplankton taxa
in a CCA biplot of sampling zone 4.

CONCLUSIONS

The water quality of the upper Ravi River is capable of supporting a diverse range of freshwater biodiversity. Based on the current research, it can be concluded that while the water quality and phytoplankton assemblage in all selected zones were good, the water quality and plankton diversity in sampling zone 3 decline, trending toward the deprived water quality category.

Based on the present findings, the condition of Ravi River can be categorized as having good water quality. While some water-quality parameters indicated decreasing trends, they remained within the acceptable limits. Sampling station 3 recorded higher values for all measured parameters compared to the other sampling zones. The study also highlights that certain development activities, particularly the construction of dam, barrages, and riverbed mining have altered the water quality at station 3. Other factors, such as the hydrology of the river, have an immense impact on the water quality and plankton diversity in the river, suggesting that futher research could deepen our understanding in this area. These types of activities will need regular scientific monitoring and should be strictly regulated. In this context, "National Water Mission" outlines key strategies to ensure sustainable water management. This includes developing a detailed water database accessible to the public, studying climate change and its impact on natural water resources, and promoting awareness of integrated, basin-level water resource management and conservation efforts.

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ECOLOGICAL STUDY OF THE FAUNA ASSOCIATED WITH *PERINEREIS CULTRIFERA* ON THE ALGERIAN COAST

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KEYWORDS: polychaete annelids, diversity, ecological indices, Algerian coastline.

ABSTRACT

To evaluate the impacts of anthropogenic activities on the ecological diversity of fauna associated with annelids in Algeria, seven sites were included in this study: Saint-Cloud beach (Annaba), Stora beach (Skikda), Figuier beach (Boumerdes), Pointe-Pescade (Algiers), Stidia beach (Mostaganem), Bomo beach (Oran), and El-Mordjène beach (El-Kala), which served as the reference site. Water samples, polychaetes, and associated fauna were collected monthly from February 2016 to January 2017. The findings show that the collected specimens (N = 40,411) belong to 25 taxa, primarily including polychaete annelids, arthropods, molluscs, Plathelminthes, Sipuncula, and echinoderms. In conclusion, the studied sites are similar in faunal composition but different in the distribution of taxa and ecological conditions, which are influenced by the physico-chemical characteristics of the water.

RÉSUMÉ: etude ecologique de la faune associée à *Perinereis cultrifera* sur la côte algérienne.

Afin d'évaluer les impacts des activités anthropiques sur la diversité écologique de la faune associée aux annélides en Algérie, sept sites ont été inclus dans cette étude: plage de Saint-Cloud (Annaba), plage de Stora (Skikda), plage du Figuier (Boumerdes), Pointe-Pescade (Alger), plage de Stidia (Mostaganem), plage de Bomo (Oran), et plage d'El-Mordjène (El-Kala) utilisée comme site de référence. De plus, des échantillons d'eau, de polychètes et de faune associée ont été collectés mensuellement de février 2016 à janvier 2017. Les résultats montrent que les spécimens collectés (N = 40.411) appartiennent à 25 taxons, principalement: annélides polychètes, arthropodes, mollusques, Plathelminthes, Sipuncula et echinodermes. En conclusion, les sites étudiés sont similaires en termes de composition faunistique mais différents sur la repartition des taxons et présentent des différences dans les conditions écologiques, qui sont influencées par les caractéristiques physico-chimiques de l'eau.

REZUMAT: studiu ecologic al faunei asociate cu *Perinereis cultrifera* pe coasta algeriană.

Pentru a evalua impactul activităților antropice asupra diversității ecologice a faunei asociate cu anelidele din Algeria, șapte situri au fost incluse în acest studiu: plaja Saint-Cloud (Annaba), plaja Stora (Skikda), plaja Figuier (Boumerdes), Pointe-Pescade (Alger), plaja Stidia (Mostaganem), plaja Bomo (Oran) și plaja El-Mordjène (El-Kala) utilizată ca sit de referință. Probele de apă, polichetele și fauna asociată au fost colectate lunar din februarie 2016 până în ianuarie 2017. Descoperirile arată că exemplarele colectate (N = 40.411) aparțin la 25 de taxoni, incluzţnd în principal polichete anelide, artropode, moluște, platelminți, Spincula și echinoderme. În concluzie, siturile studiate sunt similare în ceea ce privește compoziția faunei, dar diferite în ceea ce privește distribuția taxonilor și prezintă diferențe în ceea ce privește condițiile ecologice, care sunt influențate de caracteristicile fizico-chimice ale apei.

INTRODUCTION

Algeria has a wide Mediterranean coastline stretching 1,622.48 km, characterized by the diversity of its physical and natural environment, as well as the variety of its natural resources, flora, and fauna (Bouroumi, 2014). The coastline is also marked by a concentration of industrial activities. Approximately 66.7% of all industrial units are located in the north of the country, with 45.22% of these units are located on the coast (Dahlab, 2023). As of the most recent estimation, more than 4,302 industrial units are located in coastal cities (year of the last estimation), compared to only 1,202 in 1993 (Bouroumi, 2014). Over a period of 20 years, the number of industrial units has almost quadrupled, demonstrating the increasingly strong pressure exerted by industrial activities on this very sensitive area. Currently, the coast is even more exposed to many forms of degradation, leading to an accelerated habitat loss, and consequently, a loss of biodiversity. These pressures are driven by anthropic induced effects of chemical pollution, high population density, and urbanization, which increased from 26% in 1962 to 61.4% in 2010 (Bencheikh et al., 2022; Bouroumi et al., 2020;Ahmed et al., 2018).

Biological indicators are increasingly used to asses environemental statues of various ecosystems (Casazza et al. 2002). Among the most important species for assessing the health of coastal ecosystems, polychaete annelids appear to be a good candidate (Sebbih et al., 2023; Bouziane et al., 2020; Del-Pilar-Ruso et al., 2008). Previous studies suggest that polychaete worms can provide baseline information to evaluate demersal fish stocks, as they are an important food source for bottom feeders and are biological parameters that show the overall fertility of aquatic sediments (Patel and Desai, 2009).

Similarly, in recent decades, the use of bioindicators in ecotoxicological studies has grown as means to estimate aquatic environments and assess the level of pressure exerted by pollution on the health of habitats before entire populations or ecosystem are affected (Sebbih et al., 2023; Boucetta et al., 2019; Amira et al., 2018).

From a technical standpoint, ecological indices are among the most effective metrics for recording changes in the composition of biological communities and for establishing the relationship between exposure (or pressure) sources and ecosystem responses (Harold, 2010).

This study aims were: a) monitor the distribution patterns of *Perinereis cultrifera* and determine the annelid-associated fauna, as well as the biodiversity characteristics of the studied sites; and b) to conduct a qualitative and quantitative analysis of the collected organisms. The specimens were collected and meticulously identified and categorized based on zoological classification. This allowed us to create a taxonomic inventory, establish their spatial distribution according to ecological factors, and analyze the structure of the populations.

MATERIAL AND METHODS

Study area

The study was conducted at seven geographically distinct sites along the Algerian coast (Fig. 1). Based on anthropogenic characteristics, the sampling sites were described as follows.

The first sampling site was El-Mordjane beach (El-Kala), the second was Saint-Cloud beach (Annaba), the third was Stora beach (Skikda), the fourth was Figuier beach (Boumerdes), the fifth was Pointe-Pescade (Algiers), the sixth was Stidia beach (Mostaganem), and the seventh was Bomo beach (Oran).

The El-Mordjane site is on the beach near the town of El-Kala, approximately 25 km from the Tunisian border. This site is characterized by the dominance of granite in the composition of the rocks in the intertidal zone, and by Numidian sandstones (Baoult, 1974). It is known for its high biological diversity and is therefore considered a reference station in our present work and in several other studies (Meghlaoui, 2015; Daas et al., 2011).

The Saint-Claud site in Annaba is located 80 km west of El-Kala. The pavement and benches are composed of metamorphic rocks, primarily gneiss and quartzite. This site is located in the heart of the city, close to urban waste during the winter and to a large population in the summer (Khaled-Khodja and Rouibah, 2018). Stora beach, located in Skikda near the town's fishing port, is primarily composed of Paleozoic and Proterozoic gneiss from the Kabyle basement (Baoult, 1974). This beach is affected by pollution from port activities and urban waste.

Figuier beach in Boumerdes is located 60 km east of the capital. This beach is a strip of coarse sand rich in shellfish, with a low population during the autumn, winter and spring seasons, far from urban discharges.

In Algiers, the capital of the country, where urban density is highest, the Pointe-Pescade site is located in the city center, on one of Algiers' former communes. This site is characterized by large slabs of rock and urban waste.

Stidia Beach in Mostaganem, 80 km from Oran, features a diverse substrate of sand, mud, and stones. This station is known for its high biological diversity and low neighboring population density, making it a popular area for amateur line fishing.

Finally, Oran, located 100 km from the Moroccan border, is the most important city in the west. The Bomo site is a wide beach with fine sand rich in shell debris, with large rocks, and several sources of urban waste, particularly during the winter.

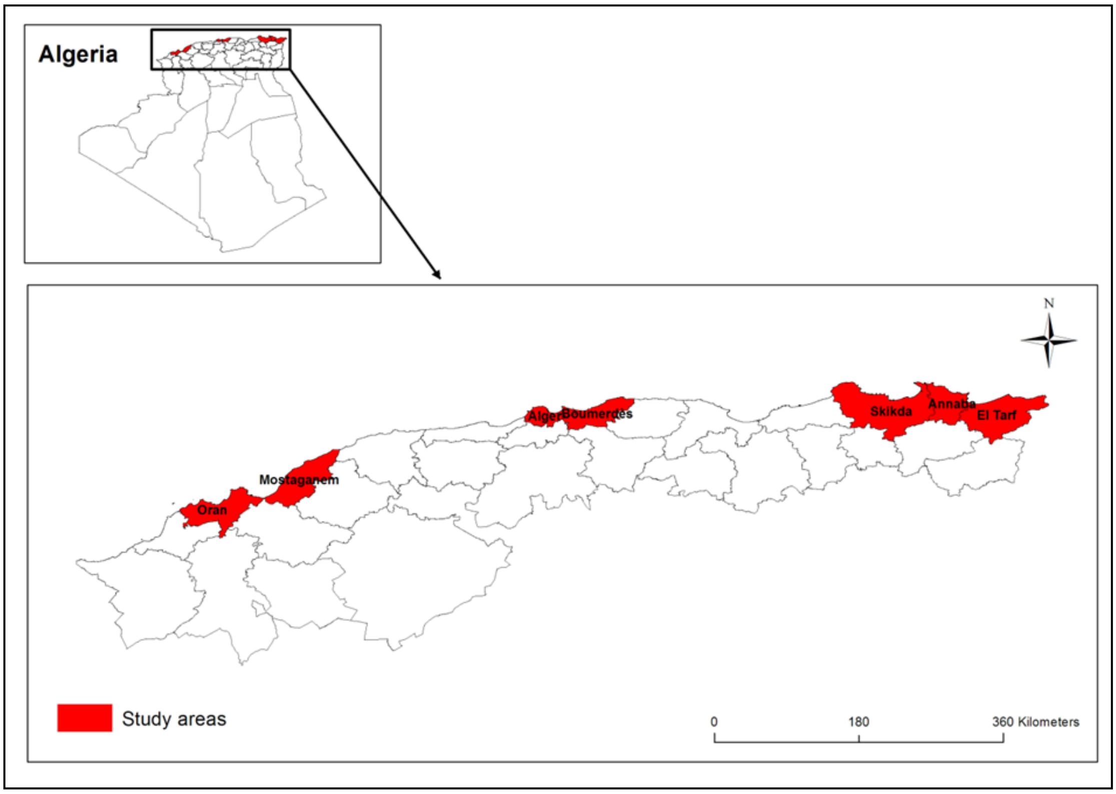

Figure 1: Map showing the locations of the coastal sites investigated;
map created using the Free and Open Source QGIS.

Physicochemical characteristics of seawater

During sampling, the maximum tidal range in these regions was approximately one meter (Rouabah and Scaps, 2003). Four physico-chemical parameters were recorded: daytime temperature, seawater temperature, pH, and salinity. Temperature and pH were measured using a thermometer and pH meter (pHep 5 –HANNA), while salinity was measured with a salinometer (Inolab 7110 W.T.W). Water samples were stored in plastic bottles and transported in a cool box to the biology laboratory for analysis.

Sampling collection

Monthly collections were conducted over a one year period, from February 2016 to January 2017, at all sites. The individuals were found among the Rhodophyceae (red algae) growing on pavements and rocky banks composed of various rock types, depending on the region. Sampling was carried out in intertidal and shallow subtidal zones during low tide at the seven sites. For species abundance studies, one-square-meter areas were marked out in advance. The seaweed was harvested at the base, either by hand or with a scraper. Specimens were stored in containers with cardboard galleries or natural algae at a temperature between 4°C and 12°C in iceboxes, with collection times ranging between three to five hours, depending on the weather conditions.

Systematic study method taxonomic analysis

The collected specimens were subjected to taxonomic examination at the “Biology, Water, and Environment” research laboratory at the University 8 Mai 1945 Guelma, Algeria. To create a comprehensive faunal catalogue of the taxa collected during the field survey and to determine the associated fauna, each individual organism was meticulously observed.

Polychaete annelids were classified based on their morphological characteristics, observed under a binocular magnifying glass, while detailed examination of parapodia and setae was coducted using a light microscope, following the methods described by Wilson et al. (2003), Fauchald (1977), Rouse and Fauchald (1997), and Fauvel (1923).

Ecological indices

The structure of these assemblages was examined, and various indices were calculated to assess the significance of the species, their distribution, and their affinities with other species:

- Abundance*:* number of individuals N of a species in a stand;
- Density*:* number of individuals N of a species per m^2;
- Frequency*:* ratio (%) of the number of stations where the species has been found to the total number of stations;
- Relative frequency*:* ratio (%) of the frequency of one species to the sum of the frequencies of all the species;
- Partial dominance*:* ratio (%) of the number of individuals of one species to the number of individuals of all species;
- Species richness (S): represents the number of species in the stand;
- Shannon and Weaver diversity index (H): takes into account the number of species present (n) and their respective abundance (pi),
  $$H = -\sum i{=}1\ piLog2pi$$
- Equitability (E): represents the ratio between the specific diversity measured using the Shannon and Weaver Index (H) and the maximum diversity Log2 S,
  $$H = H/Log2S.$$

Data analysisls

The descriptive analyses (physicochemical properties and species distribution) were expressed as means ± standard deviation (SD). Results were analyzed using a comparison of the means and an analysis of variance (ANOVA), followed by Tukey's test when the conditions of normality and homogeneity of variances were met.

In order to identify the different relationships between sites, centered and reduced Principal Component Analyses (PCAs) were applied. Active individuals were introduced according to the sample grouping criteria, projecting the observations from a p-dimensional space with p variables to a k-dimensional space (where $k < p$) in such a way as to retain the maximum amount of information from the initial dimensions. For each PCA, the principal components were sufficiently explanatory if their explained variance exceeds 60%. The data were processed using IBM SPSS Statistics package, version 25 (IBM SPSS, 2017). The minimum threshold of significance retained was $p < 0.05$.

RESULTS AND DISCUSSION

Distribution of *Perinereis cultrifera*

Perinereis cultrifera has a cosmopolitan distribution (Fig. 2), and this distribution varies with human activity. Annaba and Mostaganem show the highest concentrations, while Algiers has the lowest ($p < 0.05$).

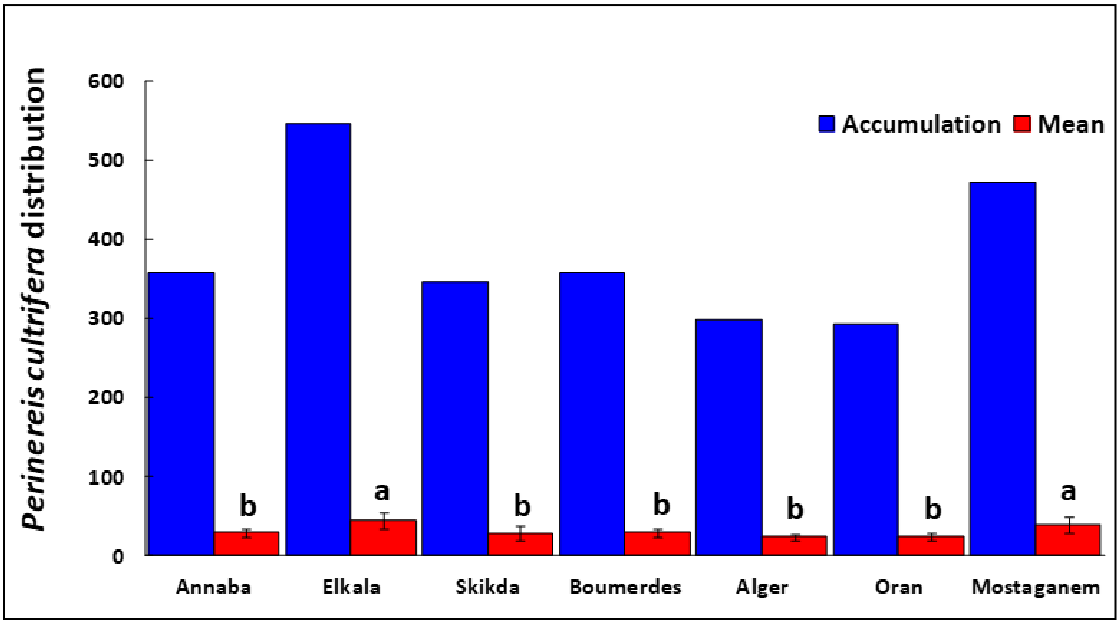

Figure 2: Distribution of *Perinereis cultrifera*.
Means are denoted by capital letters (A and B)
and indicate significant difference between locations
(Annaba, El Kala, Skikda, Boumerdes, Alger, Oran, and Mostaganem)
(Tukey's post-hoc test, $p < 0.05$).

Physico-chemical analyses

Temperature levels (Fig. 3) show variation from site to site and across seasons. The highest values were recorded at the El-Mordjène site (El Kala), ranging from an average of 19°C to 33°C in the summer. The lowest temperatures were observed at the Skikda site, ranging from 16°C to 26°C. However, the amplitudes of seawater temperature variations closely mirros the dialy variations. On average, temperatures range from 10°C in winter to 28°C in summer, with a mean annual seawater temperature of 17-21°C at the seven sites (Fig. 3).

As figure 3 shows, pH levels vary between sites. The Saint-Cloud site (Annaba) recorded the lowest average pH value over the study period, with an average of 7.51. The pH to approach normal value for seawater levels as one moves farther from industrial and urban discharge sources.

Regarding the salinity registered values, the measurements recorded during the research period varied based on geographical location. The Skikda site exhibited high salinity during the summer and autumn seasons, with a peak of 37.5 g/L in August. In contrast, salinity at the Boumerdes site decreased during the autumn and winter, reaching a lower value of 31.2 g/L in March. Overall, the water salinity measurements at the studied stations were consisten with the average salinity of Mediterranean marine waters, ranging between 33 to 37 g/L (Fig. 3).

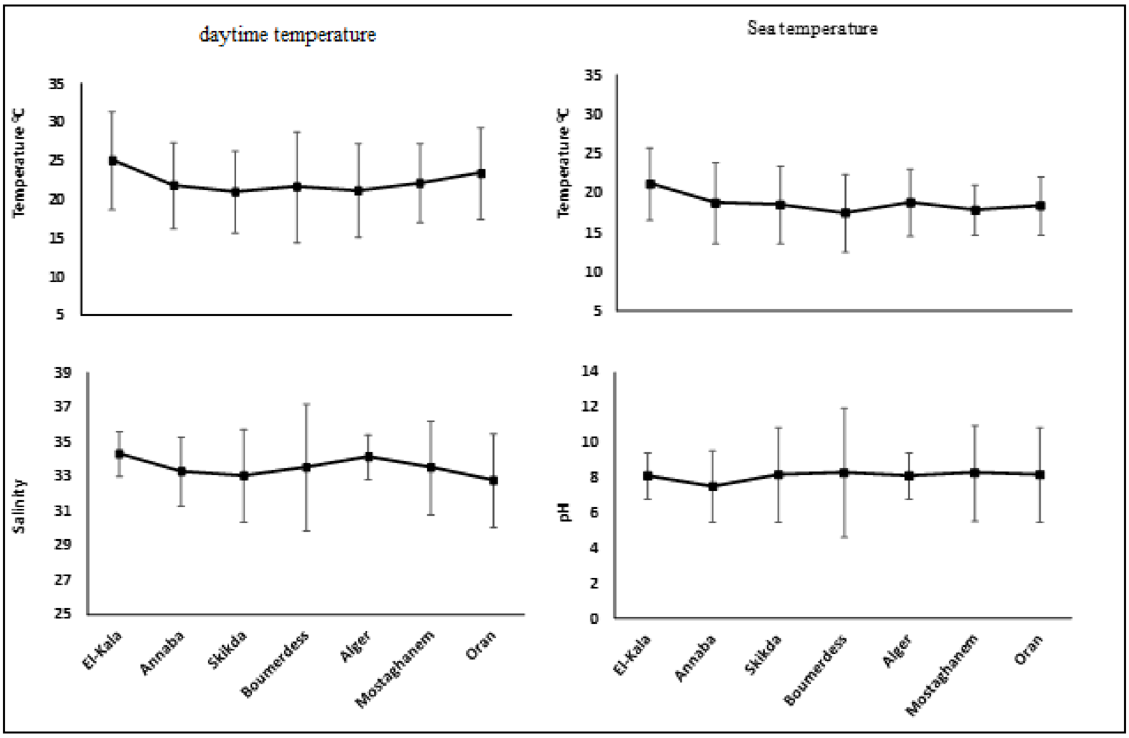

Figure 3: Variations in daytime temperature and seawater pH, and salinity at the studied sites.

The results presented in figure 4 of the Principal Component Analysis (PCA) involve seven variables (sampling sites) and four modalities (physico-chemical parameters). The first two principal components, F1 and F2, account for 50.91% and 37.27% of the variance, respectively, explaining a combined total of 88.18% of the total variability.

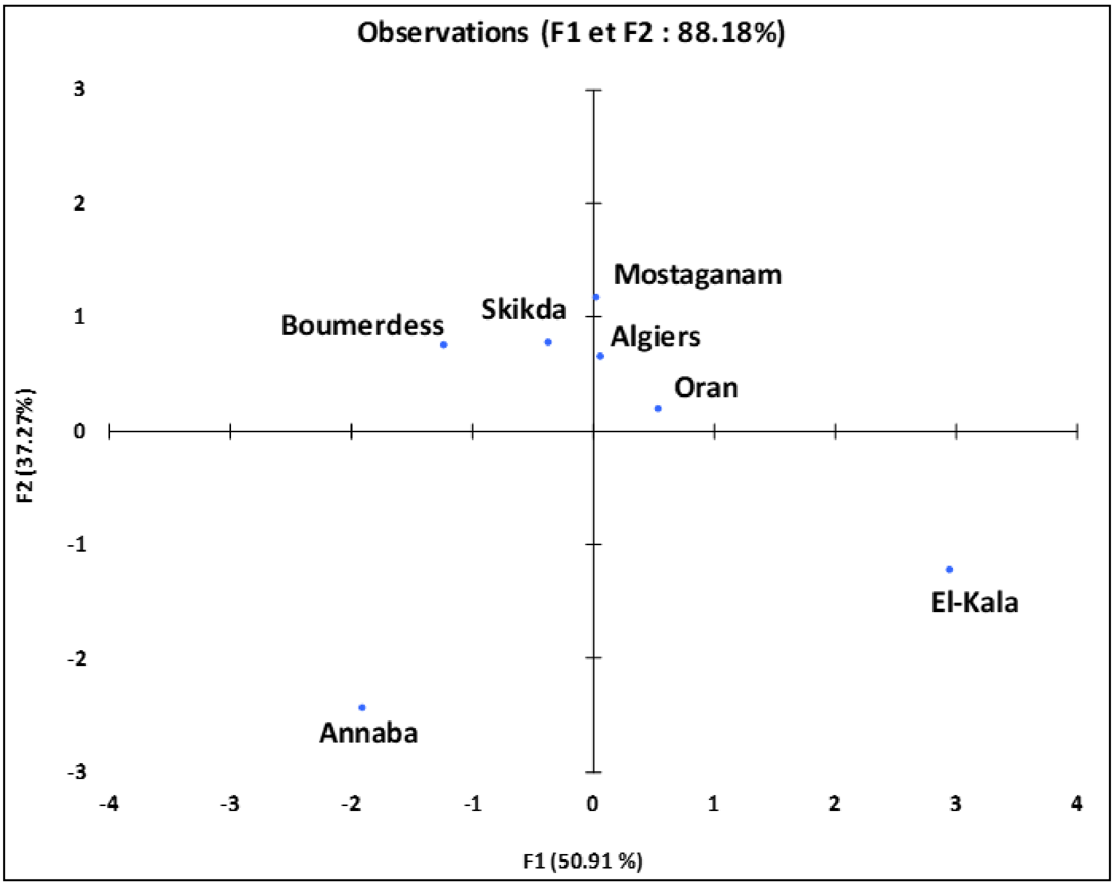

Figure 4: Principal Component Analysis (PCA).

Looking at the F2 factorial axis, we can observed that the sites are grouped into two distinct clusters. The first group consists of five sites: Skikda, Boumerdes, Algiers, Mostaganem, and Oran, which share relatively similar abiotic characteristics. The second group includes the Annaba and El Kala sites, which are geographically close to the sites in the first group.

These obtained results indicate that the physico-chemical characteristics of the Skikda, Boumerdes, Algiers, and Mostaganem researched sites are comparable, qualifying them as analogous in terms of environmental conditions. Similarly, the Annaba and El Kala sites exhibit similar characteristics that set them apart from the first identified group (Tab. 1).

Table 1: Participation rate of each factorial axis in the establishment of projection plans; Fn represents the PCA factorial axes.

F1	F2	F3	F4	F5
Eigenvalue	2.037	1.491	0.396	0.077
Variability (%)	50.915	37.265	9.893	1.927
Cumulative	50.915	88.180	98.073	100.000

The reason why the variability (%) of F1 is equal to the cumulative of F1 is due to the manner in which these values were calculated. Variability (%) of F1: The variability of F1 represents the proportion of the total variance in the data explained by the first factor (F1). In this case, F1 explains 61.059% of the total variance. Cumulative of F1**:** The cumulative for F1 is simply the sum of the variability explained by all factors up to and including F1. Since F1 is the first factor, there are no preceding factors to cumulate. Therefore, the cumulative for F1 is the variability explained by F1, which is 61.059%. For the other factors, the cumulative is the sum of the variability explained by all preceding factors plus that of the factor in question. For example, the cumulative for F2 (77.110%) is the sum of the variability explained by F1 (61.059%) and F2 (16.050%). In summary, for the first factor, the variability explained is identical to the cumulative because there is no preceding variability to add.

Ecological study

Table 2 shows a species richness of 25 taxa, distributed across the next zoological groups: polychaete annelids, arthropods, molluscs, Plathelminthes, Sipuncula, echinoderms. A comparison of species richness reveals seasonal variations and differences between the sampling sites. Arthropods and molluscs show the greatest diversity across all sites.

Table 2: Overall fauna list.

Branch	Classes	Families	Taxa
Annelids	Polychaetes	Nereidae	*Perinereis cultrifera*
			Nereis falsa
			Platynereis dumerilii
			Terebella lapidaria
		Serpulidae	*Lumbrineris* sp
			Hydroides elegans
Sipuncula	Phascolosomatidea	Phascolosomatidae	*Phascolosoma granulatum*
Plathelminthes	Rhabditophora	Pseudocerotidae	*Pseudoceros maximus*
Arthropod	Crustaceans	Malacostraca	*Paracerceis sculpta*
			Sphaeroma serratum
			Ampeliscide sp
			Eriphia verrucosa
			Gammarus pulex
		Amphithoidae	*Cymadusa hirsuta*
		Gammaridae	*Elasmopus rapax*
Molluscs	Gastropods	Mytilidae	*Modiolus modiolus*
			Mitylus galloprovincialis
			Fissurella radiosa
		Fissurellidae	*Diadora graeca*
		Veneridae	*Venerupis rhomboides*
		Patellidae	*Patella vulgata*
	Bivalves	Arcidaé	*Arca noae*
		Ostreidae	*Ostrea edulis*
	Newts	Acanthochitonidae	*Acanthochitona crinita*
Echinoderms	Echinoides	Arbaciidae	*Arbacia lixula*

Table 3 displays the distribution of species richness by species and site. *P. cultrifera* is found at all the sites, with other species whose densities vary on the locations. Based on this table, the collected taxa can be ecologically classified as follows: very low abundance taxa, such as Sipuncula and Plathelminthes, and abundant taxa, including arthropods and molluscs.

Table 3: Species distribution according to Algerian coastal sites.

Species	Sites						
	El-Kala	Annaba	Skikda	Algiers	Boumerdes	Oran	Mostaganem
Perinereis cultrifera	+++	+	+	+	+++	+	+++
Nereis falsa	+	++	+	–	–	–	–
Platynereis dumerilii	+	+	–	–	–	–	–
Terebella lapidaria	+	+	–	–	–	–	+
Lumbrineris sp.	+	–	–	–	–	–	–
Hydroides elegans	++	–	–	–	–	–	–
Phascolosoma granulatum	+	+	+	+	+	+	+
Pseudoceros maximus	+	–	–	–	–	–	+
Paracerceis sculpta	+	+	–	–	–	–	-
Sphaeroma serratum	+	+	+	+	++	+	++
Ampeliscide sp.	+	+	+	–	+	+	+
Eriphia verrucosa	++	+	+	–	-	-	+
Gammarus pulex	+	+	+	–	+	+	+
Cymadusa hirsuta	+	–	–	–	–	–	–
Elasmopus rapax	+++	+	+	–	++	+	+++
Modiolus modiolus	+	+++	++	++	++	+	+
Mytilus galloprovincialis	+	++++	++	+	+	+	+
Fissurella radiosa	++++	+	+	-	++	-	+
Diodora graeca	++	+	+	+	+	+	+
Venerupis rhomboides	+	+	+	+	+	+	+
Patella vulgata	+	+	+	+	+	+	+
Arca noae	+++	–	–	–	+	–	++
Ostrea edulis	+	+	–	–	+	+	+
Acanthochitona crinita	+++	+	+	+	++	+	+
Arbacia lixula	+	+	+	+	–	+	–

El-Kala site is notable for the high presence of *Perinereis cultrifera* within the phylum of annelids, while *Elasmopus rapax* exhibits significant density among the arthropods of this site. Among the molluscs, *Fissurella radiosa* demonstates the greatest species richness. At the Annaba site, *Nereis falsa* is the most abundant annelid, and this site is distnguished by the richness of two species: *Modiolus modiolus* and *Mytilus galloprovincialis*.

In Skikda, Algiers, and Oran, species diversity and the presence of individuals are lower compared to the two previous sites.

The last site, Mostaganem, is characterised by the dominant presence of *Perinereis cultrifera, Elasmopus rapax,* and *Arca noae*.

At the Boumerdes site, *Perinereis cultrifera, Elasmopus rapax, Modiolus modiolus, Fissurella radiosa*, and *Acanthochitona crinita* are found in large numbers. This specific species composition is unique to Boumerdes. The last site, Mostaganem, is characterised by the dominant presence of *Perinereis cultrifera, Elasmopus rapax,* and *Arca noae.*

Figure 5 illustrates the species collected along the Algerian coast, representing: annelids, molluscs, arthropods, echinoderms, Plathelminthes, and Sipuncula. The population structures vary between sites. As shown in (Fig. 5), the percentages are significantly different, with molluscs dominating at El-Kala (49%), followed by arthropods (39%), and annelids (11%), with the remaining phyla contributing smaller proportions.

At Skikda, molluscs represent the highest percentage of the total population (74%), followed by annelids (19%) and arthropods with the lowest percentage (4%). At Boumerdes, the most abundant phyla are molluscs (51%), arthropods (42%), and annelids (6%).

At the Algiers site, molluscs and annelids dominate the population, representing 45% and 40% respectively, followed by arthropods with 6%.

On the west coast, the Mostaganem and Oran researched sites show distinct population distribution. At Mostaganem arthropods consitiute 49% of the total population, with molluscs at 42% and a low presence of annelids at 8%. In contrast, at the Oran site, arthropods are the dominant phylum at 71%, followed by annelids (11%) and molluscs (9%).

Each Algerian coastal site exhibits a unique distribution of species and phyla.

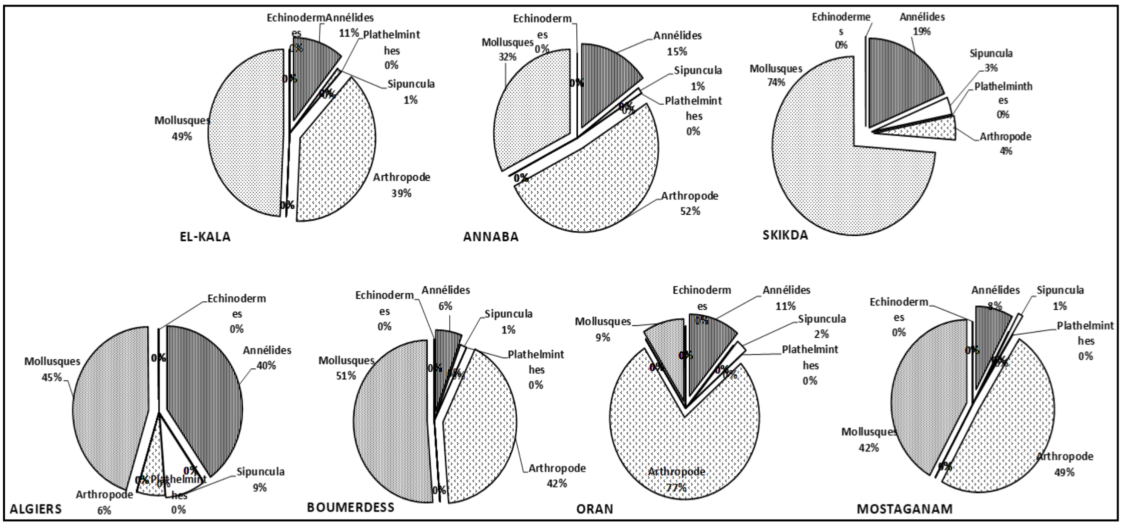

Figure 5: percentage of Algerian coastal species branches.

Abundance was highest at the El-Kala site, while the Algiers site had the lowest. El-Kala serves as the reference site, hosting 25 species, due to its geographical position and low pollution levels. In contrast, the Algiers site, with only 10 species, is located in an area with significant accumulation and high pollution.

Species diversity, as estimated by the Shannon and Weaver Index (H), ranged from 1.019 at the Oran site and 1.871 at the Annaba site. Equitability (E) varies from 0.26 at Oran to 0.43 at Annaba (Tab. 5). The Algiers site, sheltered by a natural dyke, promotes the sedimentation of organic matter, contributing to increased organic pollution.

Table 5: Abundance, richness, and specific diversity of species at Algerian coastal stations.

	Sites							
	El-Kala	Annaba	Skikda	Algiers	Boumerdes	Oran	Maostagnam	Total
Abun-dance	25	20	16	10	16	14	17	–
S	4.64	4.321	4	3.321	4	3.807	4.087	–
Log2S	1.787	1.871	1.641	1.677	1.5	1.019	1.462	–
H	0.3851293	0.4330016	0.41025	0.5049684	0.375	0.2676648	0.357719599	–
E	25	20	16	10	16	14	17	–

The coenotic affinity illustrates the degree of faunal similarity between the different sites, as represented by a dendrogram (Fig. 6), which distinguishes three distinct groups of sites. The first group includes the Algiers, Skikda, and Oran sites, with an affinity of 90% between Skikda and Oran, explained by the common species present at both sites. The second group consists of the Boumerdes and Mostaganem sites, where the affinity reaches nearly 95%. The third group comprises the Annaba and El-Kala sites. These two sites do not form a group but are linked to the previous groups, with an affinity of 25% for Annaba, and less than 10% for El Kala.

The results shown in figure 7 reflect a Principal Component Analysis (PCA) involving seven variables (sites) and twenty-five modalities (number of species). The first two axes account for 61.06% and 16.05% of the information, respectively, totaling 77.11% of the total variability. The distribution of the points on the PCA plot allows the grouping of the sites into two groups, with two additional outliers, Annaba and El-Kala. The first group consists of the Boumerdes and Mostaganem sites, while the second group includes the Algiers, Oran, and Skikda sites.

These findings align with the results of the dendrogram (Fig. 5) and the PCA of the physico-chemical parameters (Fig. 3). Additionally, the physico-chemical parameters play a crucial role in shaping distribution, presence, and abundance.

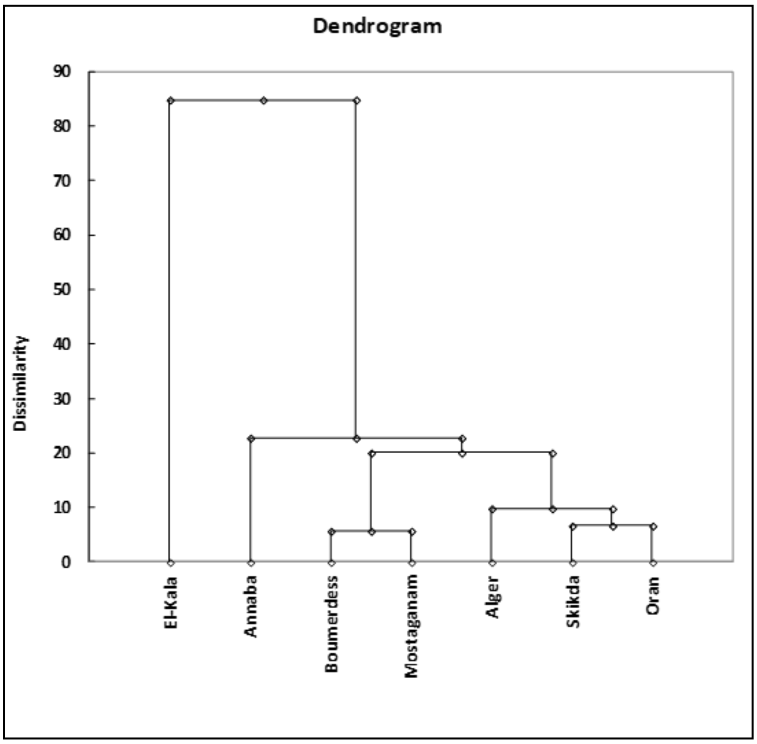

Figure 6: Inter-station dendrogram
of the Algerian coastline.

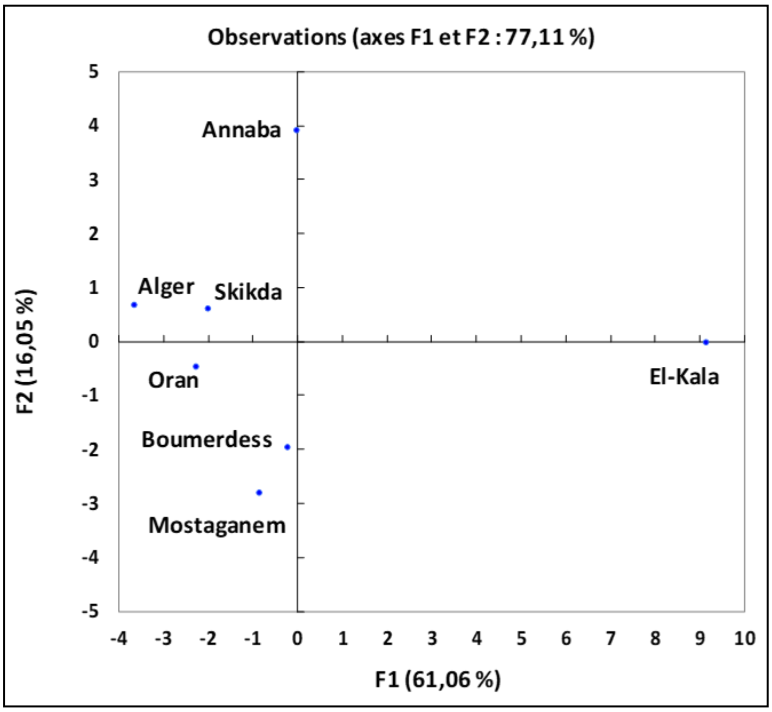

Figure 7: Principal Component Analysis (PCA).

Table 6: Participation rate of each factorial axis in the establishment of projection plans; Fn represents the PCA factorial axes.

	F1	F2	F3	F4	F5	F6
Eigen value	15.265	4.013	3.094	1.145	1.068	0.415
Variability (%)	61.059	16.050	12.376	4.582	4.272	1.660
Cumulative	61.059	77.110	89.486	94.068	98.340	100.000

The reason why the variability (%) of F1 is equal to the cumulative of F1 is due to the manner in which these values were calculated. Variability (%) of F1: The variability of F1 represents the proportion of the total variance in the data explained by the first factor (F1). In this case, F1 explains 61.059% of the total variance. Cumulative of F1: The cumulative for F1 is simply the sum of the variability explained by all factors up to and including F1. Since F1 is the first factor, there are no preceding factors to cumulate. Therefore, the cumulative for F1 is the variability explained by F1, which is 61.059%. For the other factors, the cumulative is the sum of the variability explained by all preceding factors plus that of the factor in question. For example, the cumulative for F2 (77.110%) is the sum of the variability explained by F1 (61.059%) and F2 (16.050%). In summary, for the first factor, the variability explained is identical to the cumulative because there is no preceding variability to add.

DISCUSSION

In this study, we report on the distribution of *Perinereis cultrifera* and examine the associated annelid fauna and biodiversity across seven coastal sites in Algeria. We classify the organisms by zoological group, detailing their taxonomic listing and spatial distribution. The findings indicate a cosmopolitan distribution of *Perinereis cultrifera*, which is directly linked to annual temperature variations and human activities. These results are consistent with the observations of Guemouda et al. (2014), who emphasized that habitat and pollution can significantly affect species distribution. Notably, the Annaba and Mostaganem sites show the highest densities, while Algiers exhibits the lowest. This distribution is influenced by several factors, primarily water temperature, as highlighted by Durou (2006).

Water temperature is directly linked to atmospheric temperature. The lowest temperatures were recorded in winter at the Skikda site, while the highest were observed in summer at the El-Kala site. The moderate temperatures recorded at the Stora site (Skikda) during the warm season can be attributed to marine currents that bring in masses of cold water (Bouras et al., 2007). The low pH values observed at the Annaba site can be attributed to discharges from the nearby industrial complex, which are rich in acid. In contrast, the pH trend at the other sites remains consistent with the typical values (Mehtougui et al., 2013). This finding has been corroborated by other researchers who have studied these regions (Dilem et al., 2014).

There was little variation in surface water salinity across different sites in the study area. According to the specific literature, salinity values are influenced by rainfall, industrial, and urban discharges (Remili and Kerfouf, 2013).

The Principal Component Analysis of the physico-chemical data from the seven studied sites revealeded obviously a strong correlation among the studied variables. The research results identified two principal groups of sites, with the first group consisting of five sites (Skikda, Boumerdes, Algiers, Mostaganem, and Oran) that share similar physio-chemical characteristics. The second identified group, consisting of Annaba and El Kala, displayed geographical proximity to the first found group. These findings highlight the significance of abiotic characteristics in distinguishing ecological sites, which may have important implications for species distribution and environmental specific management. These results a line with those reported by Zaabi et al. (2012, 2009). Remarkably, most of the species encountered are commonly found along all the Algerian coast. This research demonstrates the rich diversity of marine fauna along the studied Algerian coast. A total of 40,411 individuals were sampled, representing 25 species across various zoological groups. The results indicate considerable variations in diversity based on the studied sites and seasons, with certain species dominating at specific locations. The El-Kala site is characterized by its geographical position and low level of human induced pollution, as mentioned by Daas et al. (2011). Here, molluscs dominate the community, comprisisng 49% of the total, followed by arthropods at 39% and annelids at 11%. This site benefits from being naturally open with many marine currents and low annual human induced pollution (Guendouzi 2011). In contrast, the Annaba studied site is characterized by a higher presence of arthropods (52%) than molluscs (32%), with human induced pollution levels primarirly stemming from wastewater discharges from the local town and port (Guendouzi, 2011). Additionally, the population structure varies significantly among sites, resulting in significantly different percentages for the various phyla. In related research conducted among the north coast of Tunisia (Zaabi et al. 2012, 2009), a total of 88 species belonging to 29 families were recorded.

The Nereididae family accounted for only 4% of the total identified species, while Eunicidae represented 11%. In shallow water sectors, the dominant species are *Protodorvillea kefersteini* and *Malacoceros fuliginosus*, while in deep water sectors, *Aponuphis fauveli* and *Euclymene palermitana* are the most common. The main parameters influencing the distribution of benthic macrofauna along sandy coasts include physico-chemical factors, hydrodynamics, and food availability (Chaibi et al., 2018, Zaabi et al. 2009).

In summary, this research has improved our understanding of biodiversity and species distribution along the studied Algerian coast, highlighting the importance of conserving these specific ecosystems. The findings underscore the specific diversity of marine fauna in the region. The Shannon-Weaver index varies between sites, with the highest value recorded in Annaba and the lowest in Oran. Moreover, this study highlights the impact of pollution on species diversity, as evidenced by the difference between the El-Kala and Algiers sites. These results aline with those reported by Sif et al. (2012) and Rouhi et al. (2007).

CONCLUSIONS

In conclusion, the study demonstrates that abiotic factors play a significant role in shaping species distribution and abundance across various sites along the Algerian coast. The Principal Component Analysis (PCA) enabled us to identify two groups of sites, with Annaba and El-Kala notably distinct from the others. These results are consistent with those obtained in a presented dendrogram and the PCA of the physico-chemical parameters. Taking these abiotic parameters into account is essential for understanding the distribution of marine fauna along the Algerian coast, which may help in the implementation of effective conservation strategies.

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LONG-TERM MONITORING OF FISH ABUNDANCE DYNAMICS IN THE MIDDLE STRETCH OF THE MESHA RIVER (TATARSTAN)

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KEYWORDS: Mesha River, fish population, long-term abundance, long-term density dynamics, environmental factors, long-term similarity of fish populations.

ABSTRACT

The study area is located in the middle reaches of the Mesha River on the territory of the Republic of Tatarstan and is characterized by strong temporal variability in environmental factors and fish populations. The impact of environmental factors on fish species and communities was analyzed with regression and ordination methods. The dominant species were bleak, dace, chub, and roach, which together accounted for 60.7% of the total fish species. Over 15 years of research, there have been significant decreasing trends in overall density, species richness and density of individual fish species. The main factors determining the size of both the fish population and individual species were fishing effort and temperature during different months. The index of long-term similarity of fish populations was only 7.5%.

ZUSAMMENFASSUNG: Langzeitüberwachung der Fischfauna im mittleren Abschnitt des Mesha-Flusses (Tatarstan).

Es wurde der mittlere Abschnitt des Mesha-Flusses (Tatarstan) untersucht, der durch starke zeitliche Variabilität der Umweltfaktoren und der Fischpopulationen gekennzeichnet ist. Die Auswirkungen der Umweltfaktoren auf die Fischgemeinschaft wurde mithilfe von Regressions- und Ordinationsmethoden analysiert. Die dominanten Fischarten waren Ukelei, Hasel, Döbel und Plötze, die zusammen 60,7% des Gesamtbestands ausmachten. Während der 15 Jahre der Langzeitüberwachung sank der Gesamtbestand der Fische deutlich, ebenso der des Artenreichtum die Bestände der einzelnen Fischarten. Die Hauptfaktoren hierfür waren jeweils die Fischerei und die Temperatur in verschiedenen Monaten. Der Index der langzeitigen Ähnlichkeit der Fischpopulationen lag lediglich bei 7,5%.

REZUMAT: Monitorizarea pe termen lung a dinamicii abundenței peștilor în partea de mijloc a râului Mesha (Tatarstan).

Zona de studiu este situată în cursul mijlociu al râului Mesha pe teritoriul Republicii Tatarstan și se caracterizează printr-o variabilitate temporală puternică a factorilor de mediu și a populațiilor de pești. Impactul factorilor de mediu asupra speciilor și comunităților de pești a fost analizat prin metode de regresie și ordonare. Speciile dominante au fost: obletele, cleanul mic, cleanul comun și babușca. Împreună, ponderea lor a reprezentat 60,7% din inventarul total al speciilor peștilor. În peste 15 ani de cercetare, există o tendință semnificativă de scădere a densității globale, a bogăției speciilor și a densității speciilor individuale de pești. Principalii factori care determină dimensiunea atât a populației de pești, cât și a speciilor individuale au fost: efortul de pescuit și temperatura în diferite luni. Indicele similitudinii pe termen lung a populațiilor de pești a fost de numai 7,5%.

INTRODUCTION

The abundance, occurrence, distribution, and composition of individual groups of living organisms can change significantly over historical processes in aquatic ecosystems (Matthews, 1998). Temporal differences in environmental factors can have a strong impact on aquatic ecosystems (Birzaks, 2012). Changes in environmental conditions, in turn, also significantly affect species compositions (Bănăduc et al., 2024; Cianfaglione and Bănăduc, 2024; Askeyev et al., 2017) and fish population dynamics (Jeppesen et al., 2012). In modern times, ecosystems of small rivers and the organisms living in them, especially fish, which are the final ecological link and important commercial animals, are of significant interest for studying long-term population dynamics. Inland fisheries, in particular, are of general and important socio-economical interest (Lynch et al., 2016; Suuronen and Bartley, 2014). Small rivers, on the one hand, serve as a reserve for the conservation of rare and endangered species (Askeyev et al., 2021, 2017, 2015a), as well as a place for spawning grounds and the formation of biological diversity and possible corridors for invasion of alien species. On the other hand, they are subject to a whole range of stressors, from various forms of anthropogenic activities of both local and regional nature to climate warming, which can have a detrimental effect on certain groups of fish (Bănăduc et al., 2021; Buisson et al., 2013; Comte and Grenouillet, 2013) and lead to improved conditions for the existence of individual species (Daufresne and Boet, 2007). At the same time, the main focus in studying the long-term dynamics of fish abundance has been on large rivers (Bennett and Kozak, 2016; Solomon et al., 2016), reservoirs (Loures and Pompeu, 2018; Říha et al., 2009; Kuznetsov, 2005; Pivnička and Švátora, 2001; Sály at al. 2011), and lakes (Jeppesen et al., 2012), while there are practically no studies on small rivers from a temporal perspective (Askeyev et al., 2015b).

Our current study of fish populations along the Mesha River is a continuation of work by Askeyev et al. (2015b), which showed that even over a relatively short period, significant changes can occur in fish assemblages. The selected section is located 35 km east of Kazan, the capital of the Republic of Tatarstan, and is currently subject to increasing anthropogenic and fishing pressure. The climate in the Republic of Tatarstan continues to change toward warming (Askeyev et al., 2022, 2020). For example, 2020 was the warmest year in the history of meteorological observations in the Republic of Tatarstan and caused serious nonlinear reactions in phenology (Askeyev et al., 2022). Therefore, it is very important to understand the changes occurring in species composition and population dynamics, both at the population level and for individual fish species.

In this work, we set several goals: 1) To study the species composition and structure of the fish population in the Mesha River site over 15 years; 2) to assess patterns and trends in long-term dynamics of both the total number of fish and individual species; 3) to identify environmental factors influencing changes in the long-term dynamics of fish populations; and 4) to analyze the long-term variability of fish populations.

MATERIAL AND METHODS

Study area

The studied area is located in the lower part of the middle stretch of the Mesha River in the extreme east of the European continent, within the territory of the Russian Federation, on the border of two regions of the Republic of Tatarstan – Pestrechinsky and Laishevsky, near three settlements – Karpovka, Bima, and Togashevo, which are 35 km east of Kazan, the capital of the Republic of Tatarstan (Fig. 1). The elevation is 54 m above sea level (Minnikhanov, 2005). The current speed at the site is 0.1 m/s in the reaches and up to 0.5 m/s in the rifts. The depth of the river in the study area averages 1-1.2 m. The average width of the river in the study area is 25 m. The trees and bush cover 20-25% the left bank and 65-70% the right bank. The right bank section of the floodplain is significantly swampy. The composition of woody coastal vegetation is dominated by various species willows (*Salix* sp.). A few trees are also present on the site, including elms (*Ulmus* sp.) and black alder (*Alnus glutinosa)* ((L.) Gaertn., 1791). The bottom of the river section under study is primarily covered with fine-grained sand and, in places, with soft muds.

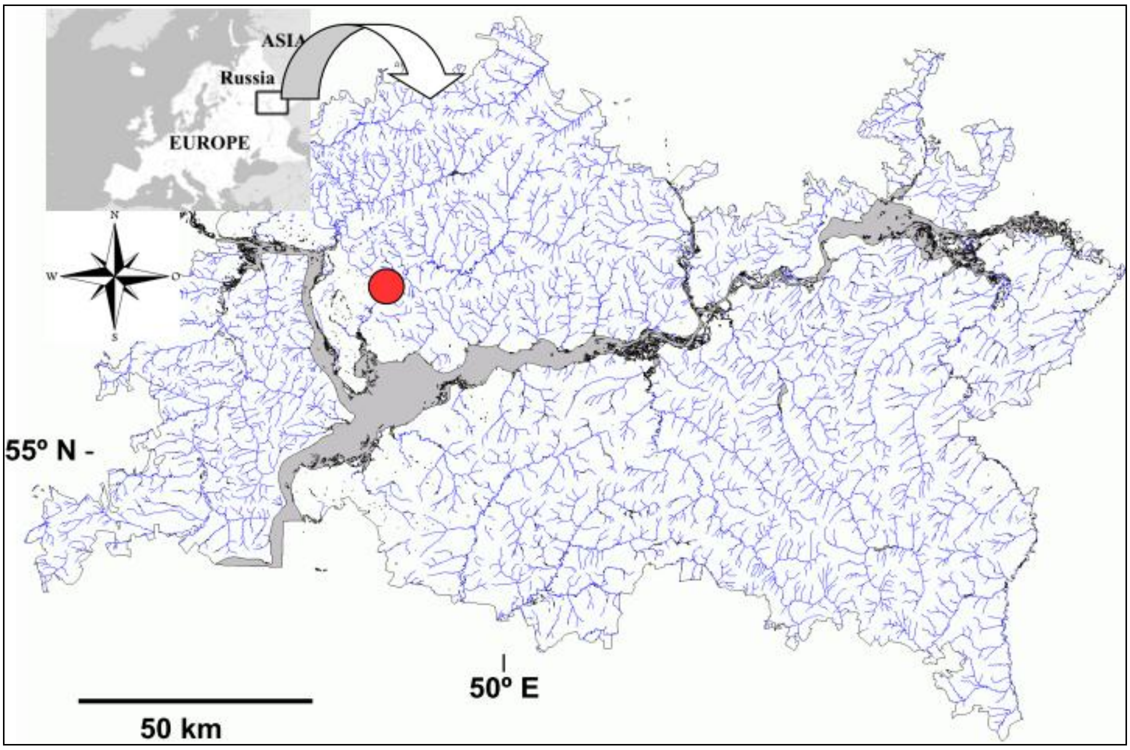

Figure 1: Map of the Republic of Tatarstan.
The red circle shows the study area on Mesha River. (inset shows location within Europe).

Fish assemblage data

Ichthyological material was collected annually for 15 years (2009-2023) from May to August, twice a month, on a 400 m long section of the Mesha River. Fish were captured using a large-mesh fry drag net 5-15 m long (with a mesh in the wings of 5 x 5 mm, in the codend 3 x 3 mm) and fishing nets (net diameter 40-50 cm, with mesh 4 x 4 mm). This set of fishing gear was selected due to significant overgrowth of the banks, the presence of rifts and the rapid change of fish biotopes. Local and short-term changes in the hydrological regime, increasing the river flow speed and water level, also influenced the choice of fishing gear (Matthews, 1998). The abundance of fish species in the area was assessed by the number of caught specimens during the fishing period, which lasted 2-3 hours in all cases. The total abundance of each species captured in a given year was then expressed as density (number of individuals per hectare). For each individual year, species richness and the Shannon index of biological diversity (H') were calculated. For each individual fish species, the mean density ± SE and the percentage from total density in the fish population were also calculated for all 15 years of study. To assess the relative abundance of a species in catches, the following classification was used: rare species – 0.01-0.50%, small – 0.51-4.99%, common – 5.0-9.9%, numerous (dominant) – 10.0-49.9%, very numerous (superdominant) – >50% of the total number in catches. Ecotopic characteristics based on abundance data are provided to describe fish population structure (Noble and Cowx, 2002). The following eight environmental factors were selected as the main variables influencing the long-term population dynamics in the selected section of the Mesha River: water temperatures for individual months (April, May, June, July, and August), the average temperature of the summer period (from April to August), spring flood levels (in m), and fishing effort, which was estimated by the number of fishermen (fishermen km^{-2}) each week throughout the entire study period. Meteorological parameters (water temperatures) were obtained from the Laishevo station.

Data analysis

Changes in densities of each species, total density, Shannon Index values, ecotopic groups of fish, and species richness over time were assessed using linear regression. The nature and strength of relationships between total density, species richness, ecotopic groups of fish and the eight environmental parameters were examined using a generalized linear model with a normal error structure. The best-fit model was selected based on the Akaike Information Criterion (AIC), with the model having the lowest AIC value considered the best fit.

We used Principal Component Analysis (PCA) to determine the similarity of long-term fish population dynamics across species. Redundancy Analysis (RDA) was then employed to study the factors influencing fish species density. In this analysis, we studied the effect of the following environmental variables on long-term abundance of fish species. Only species comprising more than 0.5% of the fish population were included in the analysis. Thus, the data matrix consisted of eight environmental factors and 16 fish species. In prior work (Askeyev et al., 2021), the occurrence of predatory fish was found to depend strongly on the species richness and abundance at the sites. Therefore, for three rare predatory fish species (asp, pikeperch, and pike), as well as three rare species (volga nase, amur bitterling, and spirlin) listed in the Red Book of the region (2016), we analyzed their populations using a generalized linear model with a normal error structure with the inclusion of total abundance and species richness of species as additional factors. The best-fit model was selected based on Akaike Information Criterion (AIC), where the model with the lowest AIC value considered the best fit. Long-term variability in the fish population was analyzed using similarity indices, calculated according to the Jaccard and Koch formulas, using the principle of minimum quantitative indicators (Chernov, 1971). Calculation and visualization were performed using PAST version 4.12 (Hammer et al., 2001), MINITAB 19 and XLSTAT 2021.

RESULTS

General information about fish populations for 15 years

In total, thirty species of fish were caught during the study period (species Latin and common names of fish are given in table 1). Of these, three species – common spirlin, Volga nase and Amur bitterling – are listed in Red Book of Republic of Tatarstan (2016). Species richness varied across the years, ranging from 16 to 25 species (with an average of 19.2 ± 0.68). The density of fish in the study area ranged from 360 to 3,640 individuals per hectare (with an average of 1,749.1 ± 276.9). The Shannon index for the site ranged from 1.818 to 2.598 (with an average of 2.13 ± 0.06). The dominant species in the studied area were bleak, common dace, chub, and roach (Fig. 2), with together accounted for 60.7% of the total number of fish in the Mesha River section over the entire 15 years of the study. Common species in terms of densities included silver bream and white-finned gudgeon. Fish species with smaller densities included perch, common bream, common gudgeon, common ruffe, gibel, ziege, rudd, ide, Volga nase, spirlin, stone loach, and blue bream. All other fish species were classified as rare.

Table 1: A – common and Latin species names of fish, as well as abbreviations in figure 2 and 3; B – mean density ± SE; C – proportion of the species in % of the total density of fish caught.

A	B	C
Northern pike – *Esox lucius* (Linnaeus, 1758)	8.8 ± 2.4	0.50
Common bream – *Abramis brama* (Linnaeus, 1758) – Abbr	78.1 ± 27.7	4.50
White-eye bream – *Ballerus sapa* (Pallas, 1814)	1.3 ± 0.7	0.10
Blue bream – *Ballerus ballerus* (Linnaeus, 1758) – Bala	8.9 ± 4.4	0.51
Silver bream – *Blicca bjoerkna* (Linnaeus, 1758) – Blbj	156.8 ± 44.7	8.90
Crucian carp – *Carassius carassius* (Linnaeus, 1758)	0.8 ± 0.4	0.05
Gibel – *Carassius gibelio* (Bloch, 1782) – Carg	40.0 ± 25.5	2.31
Gudgeon – *Gobio gobio* (Linnaeus, 1758) – Gogo	45.3 ± 12.3	2.59
White-finned gudgeon – *Romanogobio albipinnatus* (Lukasch, 1933) – Roma	93.6 ± 39.8	5.35
Spirlin – *Alburnoides bipunctatus* (Bloch, 1782)	11.5 ± 2.9	0.66
Common bleak – *Alburnus alburnus* (Linnaeus, 1758) – Alal	430.9 ± 79.3	24.6
Sunbleak – *Leucaspius delineatus* (Heckel, 1843)	7.7 ± 3.7	0.44
Asp – *Leuciscus aspius* (Linnaeus, 1758)	7.7 ± 2.2	0.44
Volga nase – *Chondrostoma variabile (volgensis*) (Jakovlev, 1870)	12.5 ± 8.1	0.71
Ide – *Leuciscus idus* (Linnaeus, 1758) – Leid	18.1 ± 7.1	1.04
Common dace – *Leuciscus leuciscus* (Linnaeus, 1758) – Lele	238.1 ± 67.8	13.6
Roach – *Rutilus rutilus* (Linnaeus, 1758) – Ruru	181.9 ± 38.8	10.4
Rudd – *Scardinius erythrophthalmus* (Linnaeus, 1758) – Scer	18.7 ± 7.2	1.05
Common chub – *Squalius cephalus* (Linnaeus, 1758) – Sqce	212.0 ± 46.6	12.1
Ziege – *Pelecus cultratus* (Linnaeus, 1758) – Pecu	24.5 ± 20.7	1.43
Tench – *Tinca tinca* (Linnaeus, 1758)	0.3 ± 0.3	0.02
Amur bitterling – *Rhodeus amarus* (Bloch, 1782)	2.1 ± 1.5	0.12
Eurasian carp – *Cyprinus carpio* (Linnaeus, 1758)	2.1 ± 1.9	0.12
Siberian spined loach – *Cobitis melanoleuca* (Nichols, 1925)	6.4 ± 1.2	0.36
Spined loach – *Cobitis taenia* (Linnaeus, 1758)	5.9 ± 2.5	0.33
Stone loach – *Barbatula barbatula* (Linnaeus, 1758) – Baba	10.1 ± 3.8	0.57
European perch – *Perca fluviatilis* (Linnaeus, 1758) – Pefl	78.4 ± 22.5	4.50
Ruffe – Gymnocephalus cernuus (Linnaeus, 1758) – Gyce	43.5 ± 23.0	2.50
Pikeperch – *Sander lucioperca* (Linnaeus, 1758)	4.0 ± 2.2	0.22
Amur sleeper – *Perccottus glenii* (Dybowski, 1877)	0.5 ± 0.5	0.03

Figure 2: Dominant fish species
(from top to bottom: common chub, roach, common dace)
on the Mesha River section.

Long-term dynamics of fish density

Significant changes in the density of eight fish species were observed over the 15-years period (Tab. 2). Six species – common bream, white-eye bream, silver bream, crucian carp, rudd and perch – showed a trend of a significant decrease in numbers (Tab. 2). While the most numerous species on the site, such as bleak, chub, and roach, also exhibited a strong downward trend, these trend were masked by annual fluctuations in their abundance. Overall, the total density of fish and species richness during the study period showed a significant downward trend. In contrast, two species of rare fish in the Republic of Tatarstan – spirlin and bitterling – displayed a significant increase in abundance.

Table 2: Changes in fish populations in 2009-2023. Regression coefficients (b ± SE) represent changes in fish density per year. Statistically significant changes are shown in bold.

Species	B ± SE	P
Northern pike	-0.01 ± 0.57	0.78
Common bream	**-16.2 ± 4.9**	**0.005**
White-eye bream	**-0.3 ± 0.12**	**0.01**
Blue bream	1.8 ± 0.94	0.07
Silver bream	**-18.1 ± 7.3**	**0.002**
Crucian carp	**-0.2 ± 0.09**	**0.05**
Gibel	-5.8 ± 3.9	0.34
Gudgeon	3.0 ± 2.43	0.31
White-finned gudgeon	-3.5 ± 9.49	0.71
Spirlin	**1.3 ± 0.59**	**0.04**
Common bleak	-21.9 ± 9.90	0.08
Sunbleak	-0.50 ± 0.27	0.61
Asp	-0.51 ± 0.52	0.39
Volga nase	2.28 ± 1.83	0.22
Ide	-1.30 ± 0.60	0.44
Common dace	20.61 ± 7.49	0.21
Roach	-15.80 ± 8.20	0.08
Rudd	**-4.01 ± 1.3**	**0.01**
Common chub	-20.31 ± 9.69	0.06
Ziege	-3.90 ± 2.91	0.44
Amur bitterling	**0.75 ± 0.29**	**0.02**
Eurasian carp	-0.44 ± 0.41	0.32
Siberian spined loach	0.02 ± 0.29	0.92
Spined loach	-0.33 ± 0.59	0.59
Stone loach	0.10 ± 0.92	0.92
European perch	**-9.92 ± 4.67**	**0.05**
Ruffe	-7.10 ± 5.17	0.19
Pikeperch	-0.80 ± 0.47	0.09
Species richness	**-0.31 ± 0.14**	**0.04**
Value of Shannon index	-0.01 ± 0.01	0.43
Total density	**-121.4 ± 57.35**	**0.05**

Interannual similarities and differences in long-term dynamics

The first two components of the PCA analysis explained 60.5% of the total variance in the long-term population dynamics of 16 fish species. The first axis, which explained 41.1% of the matrix variation, was significantly correlated with 12 fish species (Fig. 3). The second axis explained 19.4% of the variation and seven fish species were significantly associated with this axis. The arrangement of years (left to right) along the first axis clearly showed the change in fish abundance over time. On the left side we see years with small abundances, and on the right side we see years with large abundances for most of the studied fish species (Fig. 3). The second axis reflects the species-specific preferences in response to the environmental factors.

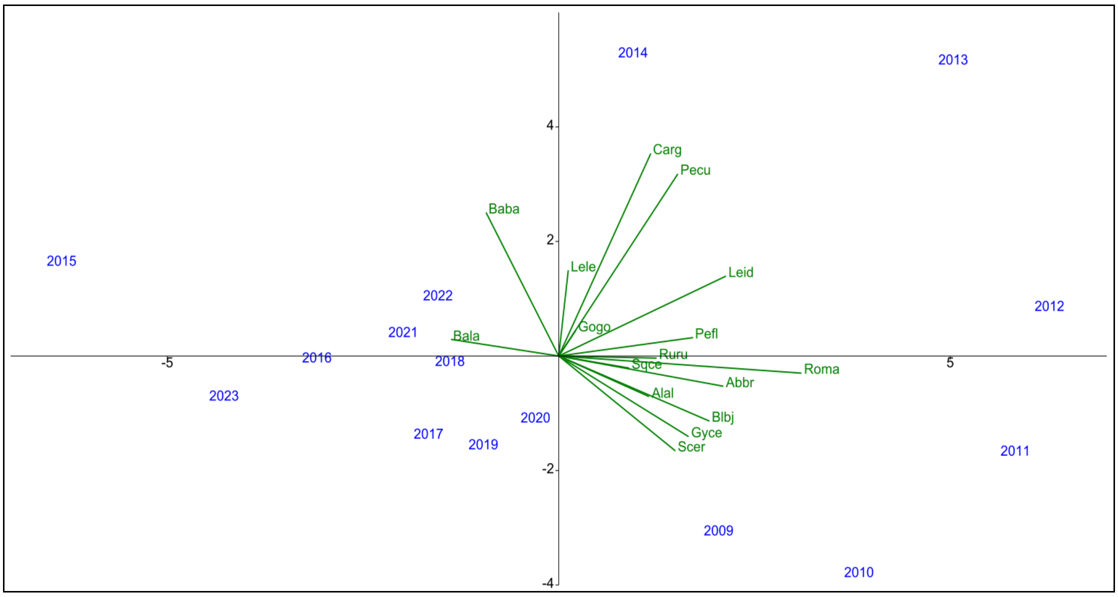

Figure 3: Biplots of Principal Component Analysis (PCA) a performed-on time series of 16 the fish species abundance in 2009-2023 years on Mesha River. Species presented as vectors and abbreviation (Tab. 1).

Compositions of fish species across environmental gradients

The first two axes of the RDA ordination explained 76.16% of the variation in the distance matrix. The first axis of ordination explained 46.83% of the variations in the researched fish assemblage's composition and was significantly related to the gradient of fishing effort and the month of July temperature ($p < 0.001$), with a lesser contribution from the overall summer (Fig. 4). The second axis explained 29.33% of the variations and was predominantly associated with spring months ' floods and May and June temperatures ($p < 0.05$).

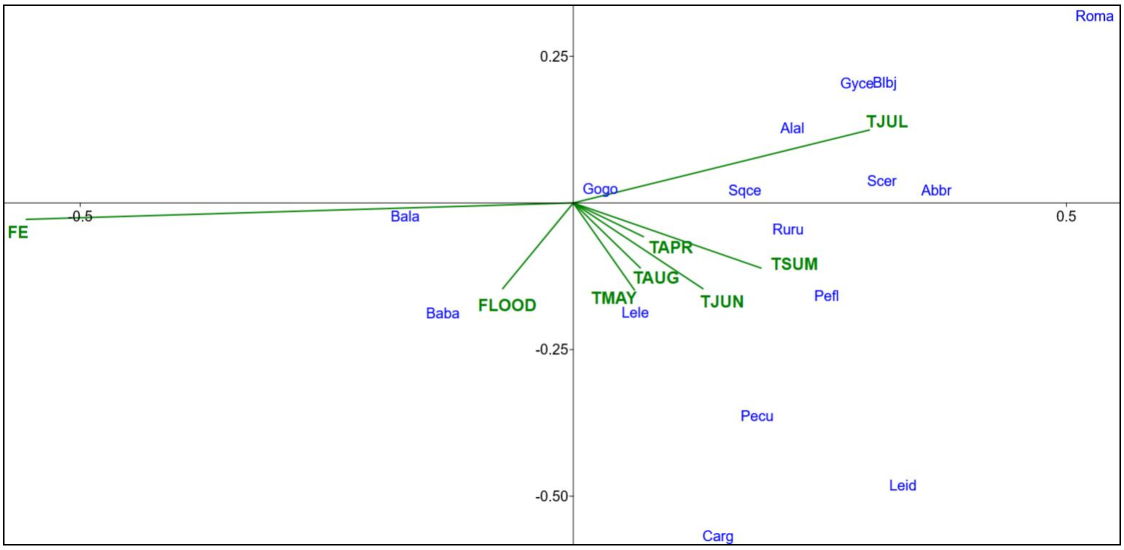

Figure 4: Biplot of first versus second axes of Redundancy Analysis (RDA), showing the relative influence on 16 fish species abundance in Mesha River of each variable. Variable represented as vectors and abbreviation: mean Summer (April-August) temperature (TSUM), temperature of April (TAPR), temperature of May (TMAY), temperature of June (TJUN), temperature of July (TJUL), temperature of August (TAUG), water flood in spring (FLOOD), fishing effort (FE). Species presented as abbreviation (Tab. 1).

In general, moving from right to left along the first axis shows a decrease in July and summer temperatures and an increase in fishing effort. The species that favored strong fishing effort was the blue bream. In contrast, whitefin gudgeon, perch, ruffe, rudd, roach, ide, bleak, silver bream, and common bream tended to avoid strong fishing effort. For bleak, ruffe, silver bream, and whitefin gudgeon, elevated July temperatures had a significant positive effect, and for roach and perch the temperature of the entire summer period had a positive effect (Fig. 4).

The second axis primarily reflected the influence of spring flood levels, as well as May and June temperatures (Fig. 4). Separate positions on this axis were identified for the stone loach, which favors years with high floods, whereas the whitefin gudgeon avoided years with high water levels in the spring. The dace showed preference for high floods and warmer May temperatures. Ziege, gibel and idefavored warmer water in both May and June.

Relationship between predatory and rare fish species and factors

Five out of ten factors significantly influenced the long-term dynamics of six rare species in the studied section (Tab. 3). Asp, Volga nase and bitterling, showed a significant positive association with temperature in May, indicating that higher temperatures corresponded to increased numbers of these species. Two species, pike and asp, were associated with fishing effort, total abundance, and species richness at the site, demonstrating that the number of pike and asp is greater in years with a higher total number of fish species. Conversely, spirlin had the opposite preference. The abundance of pikeperch also had a strong connection with human impact, indicating that the higher the human impact, the lower the abundance of this species. The abundance of bitterling, however, was higher in years with high human impact. Additionally, July temperatures significantly influenced the long-term dynamics of the asp population, with higher the temperatures leading to greater numbers of this species (Tab. 3).

Table 3: Coefficients and model summary for the relationship between abundance of six fish species and environmental variables. Environmental factors included in models are abbreviated as follows: Temperature of May (Tmay); Temperature of July (Tjul); Total density (Dens); Species richness (Spec); fishing effort (FE).

Species	Const	FE	Dens	Spec	Tmay	Tjul	AIC	p
Pike	–1.66	–	–	0.23	–	–	31.13	0.02
Asp	–6.28	–	–	0.31	0.25	0.21	45.41	0.001
Pikeperch	26.43	–0.8	0.2	–	–	–	49.83	0.01
Volga nase	–11.3	–	–	–	0.3	–	43.33	0.04
Spirlin	–4.1	–	–0.8	–	–	–	51.42	0.05
Bitterling	–6.13	1.7	–	–	0.21	–	43.08	0.005

Relationship between total abundance, species richness and environmental variables

Total abundance and species richness were strongly and significantly negatively associated with fishing effort. The greater the fishing effort on a river site, the lower the total abundance and species richness (Tab. 4).

Table 4: Coefficients for models summarizing the relationship between total abundance, total number of fish species and environmental factors. The environmental factors included in the models are abbreviated as: fishing effort (FE).

	Const	FE	AIC	p
Total abundance	9.8	–0.7	13.82	<0.001
Species richness	26.3	–1.9	45.41	0.008

Ecotopic groups of fish and their relationship with environmental factors

In the Mesha River section, three ecotopic guilds were identified: rheophiles, eurytopes, and limnophiles. Across most year of the study, except for four, the fish population was dominated by representatives of the eurytopic guild – together their share was 58.5 ± 4.7% (mean ± SE) of the total abundance. Rheophiles accounted for 39.3 ± 3.8% (mean ± SE), while limnophiles represented only 2.2 ± 0.7% (mean ± SE) and never exceeded 10% in any year. Despite the dominance of eurytopes in the population, their proportion significantly decreased over the years (B ± SE = –4.1 ± 0.9, $p < 0.001$), while the proportion of rheophiles significantly increases (B ± SE = 3.9 ± 0.9, $p = 0.005$).

Fishing effort had a significant impact on both groups (Tab. 5), though its influence was strictly opposite. In years with high fishing effort, the proportion of eurytopes decreased, while the proportion rheophiles increases. Another factor that greatly influences the abundance of rheophiles is floods. In years with high floods, the proportion of rheophiles is higher. The proportion of limnophiles was positively associated with May temperature. The higher the temperature in May, the higher the relative abundance of these group (Tab. 5).

Table 5: Coefficients for models summarizing the relationship between fish ecotopic groups and environmental variables. The environmental factors included in the models are abbreviated as: spring flood (Flood), Temperature of May (Tmay) and fishing effort (FE).

Ecotopic group	Const	FE	Flood	Tmay	AIC	p
Rheophiles	–17.9	8.9	8.6	–	130.12	0.01
Eurytopes	118.8	–9.7	–	–	139.21	0.009
Limnophiles	–8.1	–	–	3.5	124.91	0.04

Long-term similarity of fish populations

The index of long-term similarity in the fish population over the 15-year study was just 7.5%. Among the 30 species of fish recorded, only bream, silver bream, bleak, dace, chub, roach, common gudgeon, pike, and perch were recorded consistently during all 15 years of research.

DISCUSSION

Our study aims to address the gap in knowledge about the long-term dynamics of fish abundance in small rivers, highlighting strong processes of population fluctuations over a relatively short period due to climatic and anthropogenic factors. Many fish species are experiencing a strong negative impact, leading to decline in the total number of fish and individual species.

During the study period, a total of 30 species of fish were caught in the Mesha River section, representing 75% of the species richness of all small rivers in the Republic of Tatarstan (Askeyev et al., 2015a). The composition of dominant fish species, in terms of abundance, is atypical for small rivers of Tatarstan (Askeyev et al., 2015a). In particular, the shares of common gudgeon and stone loach are small and do not exceed 3%. Additionally, in a section of the Mesha River there is a complete absence of common minnow, which is the most numerous species of small rivers in the extreme eastern European subcontinent (Askeyev et al., 2017, 2015a) and Great Britain (Pretty et al., 2003). We attribute this absence to the low elevation of the location of the site and to the lack of stone substrates necessary for the species to reproduce. Comparing the species composition and dominant fish species abundance with other parts of the European continent, we see that they vary greatly in different river basins. So, it is interesting to note that similar species and numerical composition of fish to our data was obtained in the middle reaches of the Elbe River in the Czech Republic (Jurajda et al., 2010). The composition of dominant species was also similar. In particular, bleak, chub, and roach dominate in abundance. This contrasts from long-term data in the reservoir (Pivnička and Švátora, 2001), where only roach dominate in abundance. In the rivers of Hungary (Sály et al., 2011), on the one hand, there are high numbers of chub, roach, and silver crucian carp, similar to our findings. However, in the Hungarian rivers, there are numerous minnows and stone moroko (*Pseudorasbora parva* Temminck and Schlegel, 1846), which are absent in the section of the Mesha River. Conversly, Hungrary lacks dace, which is a dominant species in Mesha.

The species composition of dominant species in the section of the Mesha River differs significantly from small rivers in Latvia (Birzaks, 2012), where the dominant species are stone loach, common gudgeon, minnow, and brown trout (the latter two which are not found at all in the section of the Mesha River). Similarly, the composition of the dominant species in the Mesha River also differs from the rivers in Finland (Sutela et al., 2010), where the dominant species are bullhead and brown trout, which are both absent in our study area. Such differences between river basins indicate that to identify reliable trends in dynamics of the numbers of both individual species and fish populations, data must be collected from different parts of the species' range.

In general, the studied section of the Mesha River consistently exhibited higher numbers of fish species and Shannon Index values than in small rivers of the Republic of Tatarstan (Askeyev et al., 2015). The Shannon index in the Mesha River section in all years of the study was higher than that observed in different sections of the Elbe River (Jurajda et al., 2010), where it ranged from 1.49 to 1.71. The Shannon index was also lower than the Mesha at various sites in small rivers in Britain (Pretty et al., 2003), where it ranged from 1.61 to 1.82. The highest value of the Shannon Index was higher than the highest value in all small rivers in Latvia (Birzaks, 2012). The elevated value of species in the Mesha River section can be attributed to the mixing of fish from different guilds and the large number of microhabitats within a relatively short distance.

The PCA analysis showed synchronicity in population dynamics for the most numerous fish species, such as bleak, chub, roach, silver bream, bream, whitefin gudgeon, and perch. Based on these findings, we propose that in years when the density of silver breamis is high, the density of roach will be equally elevated. However, not all fish species experienced similar dynamics over the 15-year period. For example, blue bream exhibited the opposite trend in abundance compared to the above species, while dace (one of the most numerous fish species in the area), gibel, ziege, gudgeon, and stone loach held intermediate positions between these patterns.

A key question remains: what factors explain these changes in the many population dynamics. Redundancy analysis (RDA) can help address this question. Over the 15-years, multiple factors influenced the fish species in the area of the small Mesha River. The main factor influencing abundance of individual fish species was the fish effort on the site, which which had a negative impact, leading to a strong decrease populations. Human pressure could lead to a tenfold decline in abundance compared to that observed in the most productive year.

The prevalence of fishing effort over other factors has been described for lakes in Finland (Ranta et al., 1992), further supporting our thesis that excessive inland fishing (Post et al., 2008) can severely undermine the stocks of key species. This rasises serious concern, since it is shown (Daupagne et al., 2021) that the main measures to restore numbers are ineffective. In particular, stocking with non-native species can ultimately lead to an imbalance in the system (Hickley and Chare, 2004), and even stocking native species does not always provide a restoration effect or an increase in abundance (Argillier et al., 2002).

While some studies, such as Arlinghaus and Mehner (2005), highlight the selectivity of catching and reducing only species that are commercially valuable, our data suggests a reduction of, in addition to these species, less valuable and smaller-sized species. In this regard, we urge our colleagues to take a more careful and serious look at the issues of reducing even relatively insignificant species for fishing.

Contrary to fears that climate warming could lead to additional declines in fish population abundance (Buisson et al., 2013; Comte and Grenouillet, 2013), our results suggest that warming could actually contribute to an increase in the abundance of many fish species if not for the strong pressure of human activity on the site. Most fish species thrive in months with higher temperatures. These temperatures contribute to better survival of juveniles and an increase in food supply for adults. However, the importance of temperature for specific months varies for different fish species

We observed a significant decrease in abundance for perch, as well as three other less common predatory fish species. This decrease in abundance is directly associated with over-fishing, as well as a decrease in the overall abundance of species and a decrease in the number of non-predatory fish populations. The effect of a decrease in perch abundance in low abundance years has been shown in the Czech Republic (Pivnička and Švátora, 2001).

Interestingly, it was unexpected that less common species in Tatarstan, such as bitterling and spirlin, significantly increased in abundance. We believe this is related to a strong decline in the total abundance of other species of competitors and predators. Another rare species, the Volga nase, also saw an increase in numbers, but the main reason for its growth was elevated temperatures in May, coinciding with its breeding month.

The overall abundance and species richness show a significant decreasing trend, primarirly due to determining factors such as the strong fish effort. More intense floods and high river water levels in spring favor the rheophilic group of fish to spawn more efficiently, as well as the elimination of representatives of the eurytopic group due to high human pressure.

The low level of interannual similarity over the 15-year period points to strong fluctuations among the fish population, indicating that the fish are experiencing a range of stresses, which greatly influence the population dynamics of each species causing constant disruptions within fish species compositions. Such changes raise serious concern for the conservation of species diversity and rare and endangered species in this unique site of the small river, despite recent increases in abundance.

CONCLUSIONS

Unlike well-established monitoring schemes for long-term dynamics of the number of birds operating on different continents (Lehikoinen et al., 2016; Prince and Zuckerberg 2015), there are virtually no long-term monitoring schemes for fish. Our research demostates that even within the same region, the dynamics of different vertebrate groups can vary. In contrast to the number of birds in Tatarstan (Askeyev et al., 2023, 2020), which is rapidly growing in different groups, the density of fish is falling. Despite the increasing anthropogenic pressure, this section of the Mesha River is a spawning ground for many valuable commercial fish species and serves as a refugium for the conservation of three “Red Book” fish species in the Republic of Tatarstan. Thus, we see that in the extreme eastern European subcontinent, modern climate warming is having beneficial effects on different groups of vertebrates in different habitats, but for fish, this trend is masked by strong fish efforts. Notably, 2023 was the warmest year on record in the study area, emphasizing the need for careful monitoring of the state of aquatic ecosystems and the number of individual species of living.

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IGNORED DAM-FISH ECOLOGICAL RELATIONS AND DAM MANAGEMENT ACTIVITIES RISK KNOWLEDGE CAPITAL – A PROTECTED AREA LOTIC ECOSYSTEM CASE STUDY (GURA GOLUMBULUI DAM LAKE, NERA/DANUBE WATERSHED)

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KEYWORDS: fish, dam lake, river, liquid and solid flows mismanagement impact.

ABSTRACT

This work presents data on the fish identified in the lentic sector of the Golumbilor Lake and upstream and downstream lotic proximal sectors in two periods. The first is before ruthless management of the liquid and solid lake sediments (in 2022) and one after it (in 2023), presenting in a comparative way the modifications in the ichthyofaunal structure. The most striking change observed in the fish fauna of the downstream lake habitats is the replacement of fish species characteristic of lotic habitats with those typical of lentic habitats, which reflects the significant change in habitat characteristics due to this specific human impact.

RÉSUMÉ: Les relations écologiques négligées entre les poissons et les barrages ainsi que les activités de gestion des barrages mettent en péril le capital des savoir-faire – une étude de cas sur un écosystème lotique protégé (lac du barrage de Gura Golumbului, bassin versant de Nera/Danube)

Nous présentons les poissons capturés dans le secteur lénitique du lac Golumbilor et dans les secteurs lotiques proximaux en amont et en aval à deux périodes, l'une avant une gestion impitoyable des sédiments liquides et solides du lac (en 2022) et l'autre après (en 2023), en présentant de manière comparative les modifications de la structure de l'ichtyofaune. Les changements les plus marquants observés dans la faune piscicole des habitats lacustres en aval sont le remplacement de certaines espèces de poissons caractéristiques des habitats lotiques par des espèces caractéristiques des habitats lénitiques, un fait qui reflète le changement significatif des caractéristiques de l'habitat dû à cet impact spécifique de l'homme.

REZUMAT: Ignorarea relațiilor ecologice baraj-pești și a capitalului de cunoaștere legat de riscurile asociate activităților de management a barajului – studiu de caz al unui ecosistem lotic protejat (lacul de baraj Gura Golumbului, bazinul Nera/Dunăre).

Această lucrare prezintă datele despre peștii capturați în sectorul lenitic al Lacului Golumbilor și în sectoarele lotice proxime din amonte și aval în două perioade, una înainte de o gestionare brutală a debitelor lichide și solide lacustre (în 2022) și una după aceasta (în 2023), prezentând comparativ modificările ihtiofaunei. Cele mai frapante modificări observate în fauna piscicolă din habitatele din aval de lac este înlocuirea unor specii de pești caracteristici habitatelor lotice cu specii caracteristice habitatelor lenitice, fapt care reflectă modificarea majoră a caracteristicilor habitatului datorită acestui impact antropic specific.

INTRODUCTION

The ecological state of aquatic ecosystems is a fundamental aspect for environment and humans' health and well-being, which are affected in diverse ways by various crisscrosing natural and anthropogenic stressors that damage and diminish biodiversity and ecosystem structure and function (Błońska et al., 2024; Bănăduc et al., 2024, 2023, 2022).

Some high-risk environmental events are induced by humans sometimes due to the lack of know-how, sometimes ingnoring the existing know-how and even general or specific laws, including in protected areas (i.e. Natural Parks, National Parks, Natura 2000 sites, etc.), like in the case study presented in this paper. These research results are based on few years of monitoring study of the Miniș River fish fauna (Nera River Basin, Danube River Basin), accidentally surprising in this monitoring period an improper dam liquid and solid flows management event, specifically the sudden and complete discharge of sediments from the Golumbilor Dam lake (Fig. 1) into the downstream Miniș River sector.

The Golumbilor Lake anthropogenic reservoir was formed by damming the Miniș River. Located between the towns of Anina and Bozovici, the dam was built in 1985 for the water use of thermal power plant from Crivina and has a length of 750-900 m, a width of 150 m, a maximum depth of 15 m. Currently, this lake is a local tourist attraction, used for recreational activities including fishing. The lake is concessioned by a local investor.

Situated within the Cheile Nerei-Beușnița National Park, ROSCI0031 and ROSPA0020, the lake transformed the natural lotic habitat into a lentic one (Fig. 1) over the years. Over time, the lake was accidentally or intentionally stocked with different non-native fish species, characteristic of lotic habitats (Figs. 2 and 3), which are replacing the local native species characteristic of the lotic upstream and downstream Miniș River sectors.

Figure 1: The lenitic habitat of Gura Golumbilor Dam Lake.


Figure 2: The lotic habitat of Miniș River upstream Gura Golumbilor Dam Lake.


Figure 3: The lotic habitat of Miniș River downstream Gura Golumbilor Dam Lake.

Ichtyofauna faces large-scale and significant negative impacts due to human activities and changes in their habitats (Bănăduc et al., 2022; Simić et al., 2022; Zare-Shahraki et al 2022; Curtean-Bănăduc and Bănăduc, 2020; Kar, 2019; Joy et al., 2018; Curtean-Bănăduc et al., 2018, 2014, 2007; Khoshnood, 2017; Kruk et al., 2017; Marić et al., 2017; Sosai, 2015; Telcean et al., 2011; Trichkova et al., 2009; Ureche et al., 2007; Curtean-Bănăduc and Bănăduc 2006; Afanasyev, 2003; Cordone and Kelly, 1961).

Among these factors, poor dam design, construction, destruction or/and the improper regular and/or accidental liquid and solid flows management are responsible for many of the negative impacts on fish all over the world (Bănăduc et al., 2020; Hudek et al., 2020; Song et al., 2019; Rumana et al., 2015; Soolutayo, 2012; Wang et al., 2011; Agostinho et al., 2008; Afanasyev, 2003; Barrella and Petrere, 2003; Radojković et al., 2019).

Rivers and streams drain water from land to sea and oceans and thus become the main path for transporting the products of continental weathering, increased phenomena by human-related activities, such as river impoundment and changes in land use, which all together alter the sediment load in rivers (Bănăduc et al., 2020; Tena et al., 2012). As a consequence, one of the fundamental issues with the operation of surface water resources is erosion and sediment transport, reducing the reservoir's useful life cycle and/or impacting the reservoirs by different ways (Othman et al., 2013). Reservoir storage capacity is often a direct consequence of erosion and sediment deposition (Othman et al., 2013).

Preserving the natural qualitative and quantitative sediment imputs and flow in any basin is crucial for water quality and the proper functioning of the aquatic ecosystem (Lele et al., 2024) in spite of some human activities with uncontrolled negative effects (Emadak et al., 2019). Sediments play an important role in transporting nutrients and dispersing contaminants within aquatic ecosystems (Schleiss et al., 2008; Taylor, 2007), but also their quality and quantity can transform habitats drastically. Acute and chronic happenings induce changes in the sediment load regime and can have major implications for downstream channel geomorphology; although impacts vary according to the size of the watershed, river and dam, position of the dam in the catchment, hydrologic regime, and channel morphology, as well as with the types of operations in the impoundment (Williams and Wolman, 1984). In some cases, dams can reduce sediment transport across varying spatial and temporal scales, often for an extended period and over considerable downstream distances, whereas in other cases impacts are apparent only in the reach immediately downstream of the dam (Brandt, 2000).

Accidental/accidental like due to the dam liquid and solid loads poor management or the drainage of the dam lake, induced sudden and significant quantities of sediments and ecosystemic drastic changes, impacting locally important conservation and economically significant, even endemic aquatic species, including fish. As a result of draining the reservoir, the bottom of the downstream riverbed can be completely covered by a thick blanket of mud for long periods of time, which significantly deteriorates the living conditions for aquatic organisms, including fish, as well as their trophic resources in downstream river sectors (Bănăduc et al., 2020).

Habitat quality is fundamental for fish, with the physical and chemical features of the aquatic system affecting their survival, growth, reproduction, and recruitment (Bozek et al., 2011). In this general circumstance, sediments accomplish a key part in the ecology of lotic ecosystems and on the fish community structure, diversity, and abundance.

This study identified and described, during an ichthyological research in the Miniș River basin area, the negative effect of a dam lake management related risky activity on the fish faunal structure in the adjacent lotic sectors of Golumbilor Dam Lake.

MATERIAL AND METHODS

The presence/absence of fish in Miniș River and Golumbilor Dam lake was determined by electrofishing (Hans Grassl IG 600TL) (Fig. 4), in time (45 minutes)/effort unit, from every two-three km length river sector, from the river springs to its confluence with the Nera River. A total of 18 sampling stations (Fig. 5), each 100 meters in length, were surveyed. After quick visual identification, the sampled fish were released in the habitat of origin.

Figure 4: Scientific fishing using the electronarcosis method (electrofishing).

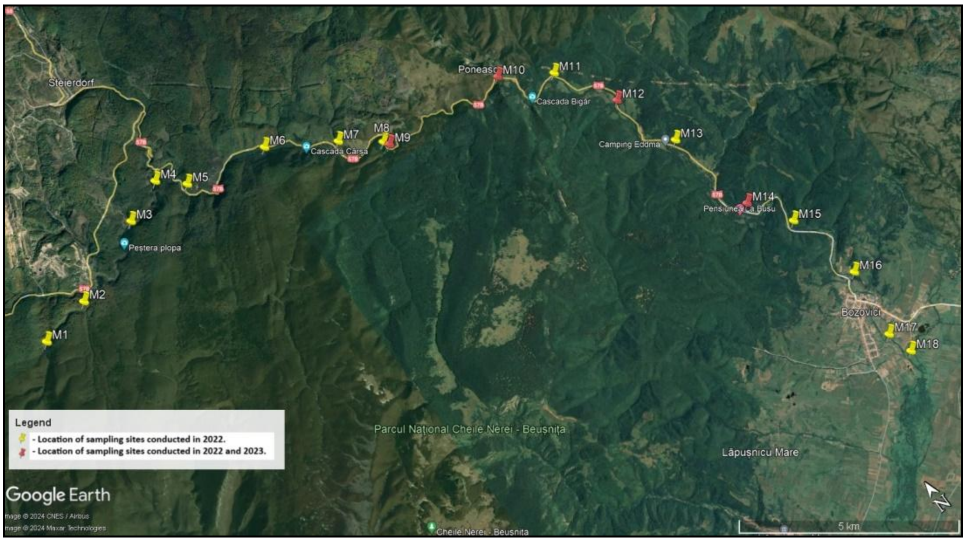

Figure 5: Sampling stations on Miniș River.

RESULTS AND DISCUSSION

This paper specifically presents the fish species identified in the lentic sector of Golumbilor Lake, as well as in the upstream and downstream lotic proximal sectors, during two distinct time periods, one before the ruthless management of the liquid and solid lake sediments (in 2022) and one after it (2023), presenting in a comparative way the modifications in the ichthyofaunal structure (Tab. 1)

This research exposed the significant negative effect of the studied dam lake's inappropriate liquid and solid flows on the downstream lotic ecosystems. The results contribute to the knowledge base on the negative potential impact of improper management of dam lakes, which is a precondition for informing decision-making for these lakes by investors, stakeholders, and managers. More knowledgeable judgments and choices can assist more well-adjusted reactions and the drifting of coordinated policies, strategies and actions to meet the problems of human-nature interrelations and aquatic biodiversity loss, in a more integrative approach, in this manner avoiding significant negative changes to lotic ecosystems.

The most striking change observed in the fish fauna of the downstream lake habitats is the replacement of fish species characteristic of lotic habitats with those typical of lentic habitats (Tab. 1).

Table 1: The fish species sampled before and after the improper management of the sediments of Gura Golumbilor Dam lake upstream of the lake (Fig. 2), in the lake (Fig. 1), and downstream of the lake (Fig. 3); B (before) – 2022, A (after) – 2023.

Species no.	Upstream lake habitat characteristics	In the lake habitat characteristics	Downstream lake habitat characteristics
–	Substrate composed of gravel, cobble and sand. Substrate covered with organic matter. Abundant riparian vegetation, in favorable condition predominantly consisting of trees, shrubs, and herbaceous plants. Stable banks, with no signs of erosion.	Substrate composed of silt and sand with aquatic vegetation. Riparian vegetation specific to the lentic ecosystem, predominantly composed of reeds and herbaceous plants, surrounded by trees. Stable banks, with no signs of erosion. The lotic ecosystem was transformed into a lentic one by damming the river with a concrete dam approximately 20 meters high. Species characteristic of stagnant aquatic ecosystems are present, including invasive species. The dam is equipped with non-functional fish ladders.	Substrate composed of boulders, rocks and gravel. The riparian habitat in favorable condition. Abundant riparian vegetation, predominantly consisting of large trees, shrubs, and herbaceous plants. Stable banks, with no signs of erosion.

Table 1 (continued): The fish species sampled before and after the improper management of the sediments of Gura Golumbilor Dam Lake upstream of the lake (Fig. 2), in the lake (Fig. 1), and downstream of the lake (Fig. 3); B (before) – 2022, A (after) – 2023.

Species no.	Upstream the lake fish species	In the lake fish species	Downstream the lake fish species
3	B-*Phoxinus phoxinus* A-*Phoxinus phoxinus*	B-*Carasius gibelio* A-*Carasius gibelio*	B-*Barbus balcanicus*
3	B-*Phoxinus phoxinus* A-*Phoxinus phoxinus*	B-*Carasius gibelio* A-*Carasius gibelio*	B-*Barbus balcanicus*
3	B-*Barbus balcanicus* A-*Barbus balcanicus*	B-*Pseudorasbora parva* A-*Pseudorasbora parva*	B-*Gobio obtusirostris* A-*Gobio gobio (*sin. *Gobio obtusirostris)*
3	B-*Barbus balcanicus* A-*Barbus balcanicus*	B-*Pseudorasbora parva* A-*Pseudorasbora parva*	B-*Gobio obtusirostris* A-*Gobio gobio (*sin. *Gobio obtusirostris)*
2	B-*Salmo trutta fario* A-*Salmo trutta fario*	B-*Phoxinus phoxinus* A-*Phoxinus phoxinus*	B-*Phoxinu phoxinus*
3	B-*Squalius cephalus* A-*Squalius cephalus*	B-*Leucaspius delineates* A-*Leucaspius delineatus*	B-*Alburnoides bipunctatus*
3	B-*Squalius cephalus* A-*Squalius cephalus*	B-*Leucaspius delineates* A-*Leucaspius delineatus*	B-*Alburnoides bipunctatus*
3	B-*Squalius cephalus* A-*Squalius cephalus*	B-*Leucaspius delineates* A-*Leucaspius delineatus*	B-*Alburnoides bipunctatus*
3	B-*Rutilus rutilus* A-*Rutilus rutilus*	B-*Squalius cephalus* A-*Squalius cephalus*	B-*Squalius cephalus*
2	–	B-*Rutilus rutilus* A-*Rutilus rutilus*	B-*Rutilus rutilus* A-*Rutilus rutilus*
2	–	B-*Ameiurus nebulosus* A-*Ameiurus nebulosus*	B-*Barbatula barbatula*
1	–	–	A-*Pseudorasbora parva*
1	–	–	A-*Carassius gibelio*

The construction of a dam transforms a free-flowing lotic sector of the Miniș River into a lentic habitat, favoring impoundment-dwelling fish species that free-flowing sectors may not naturally support. This lake is actually a sediment trap, retaining sediments which, under a wrong management, can negatively influence the downstream lotic sectors fish habitats.

This impoundment changed the landscape of the Miniș River basin, fragmenting the watershed and regulating its water and sediment flow. This relevant factor significantly impacts river ecosystems, moderately affecting the conservation of migratory fish species and the connectivity among different fish populations under normal water and sediment management conditions. However, these impacts become far more pronounced under mismanagement scenarios, as demonstrated in this study.

Management activities to reestablish healthy populations of lotic fish species, after such inappropriate human induced events, are usually very complex in terms of time and resources requirements. As such, these types of actions should be avoided whenever possible. Qualitative and quantitative analysis of the tradeoffs between a lakes' benefits for human uses and fish population recovery related to dam lake water management and decision-making is almost lacking.

On the whole, the different types of local fish communities found reveal different specific compositions, showing altered ecological status of the aquatic habitats after the impact of the dam lake liquid and solid flows mismanagement.

All such dam lakes must implement specialized liquid and solid flows management and fish monitoring systems to check and balance the local stakeholders management decisions and activities.

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