

DOI:10.5937/IIZS25405B

A MULTI-DIMENSIONAL APPROACH TO DANUBE RIVER PRESERVATION: COMBINING WATER QUALITY SCIENCE AND ACOUSTIC ART

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Abstract: This study presents an integrated environmental assessment of the Danube River at three sites near Novi Sad, Serbia, combining physicochemical water quality analysis with acoustic soundscape monitoring. Water samples collected at Burma Beach, Estuary DTD, and Resort Ribarsko Ostrvo in September 2024 were analyzed against Serbian and WHO standards. The results revealed overall high ecological status, with most parameters—including dissolved oxygen, nitrates, nitrites, and phosphorus—falling within Class I limits. However, localized exceedances in total organic carbon (TOC), ammonium, arsenic, and copper placed some samples in Class II and III, indicating moderate pressures from urban and industrial activities. Acoustic monitoring enriched the evaluation by capturing distinctive environmental soundscapes, from bird colonies and recreational noise to industrial ship traffic and underwater disturbances. These findings highlight the Danube's resilience while emphasizing the need for continuous monitoring to manage localized stressors. By combining scientific and sensory dimensions, this study demonstrates a novel interdisciplinary approach to river assessment and public environmental engagement.

Key words: Danube River, water quality, soundscape, Novi Sad, environmental monitoring

INTRODUCTION

Freshwater ecosystems provide essential services to human societies and natural biota, yet they are increasingly compromised by multiple, interacting anthropogenic pressures. Rivers are subject to nutrient enrichment from agricultural runoff, point-source discharges from industry and wastewater treatment plants, diffuse urban runoff, and physical disturbance from navigation and infrastructure development; together these stressors degrade water quality, alter biotic communities and reduce the capacity of rivers to supply safe water for drinking, recreation and ecosystem functioning [1,2]. The Danube — Europe's second-longest river and a transboundary corridor for commerce, industry and biodiversity — exemplifies these challenges because pollutants and hydromorphological pressures originating in one country propagate downstream across national borders, complicating management and remediation efforts [3].

Contemporary policy frameworks such as the European Union Water Framework Directive (WFD) require systematic monitoring and classification of ecological status to support integrated river basin management and to guide restoration measures [4]. Compliance with WFD objectives depends on robust, temporally and spatially representative data for key physicochemical and biological indicators. In parallel, there is growing recognition that non-chemical dimensions of rivers — notably their acoustic environments or "soundscapes" — convey valuable information about anthropogenic activity, habitat condition and the presence or absence of fauna; acoustic monitoring can thus complement conventional monitoring by revealing patterns of disturbance (e.g., shipping and recreational noise), biotic activity (e.g., bird and fish sounds) and human–environment interactions that are not captured by chemical analyses alone [5].

The present study adopts an interdisciplinary perspective by combining targeted physicochemical water quality assessment with systematic acoustic observations at three sites

adjacent to Novi Sad, Serbia (Burma Beach — NS3, Estuary DTD — NS2, and Resort Ribarsko Ostrvo — NS1). Field sampling and acoustic recordings were conducted in September 2024. The objectives were: (i) to evaluate local ecological status against national (Serbian) and international (WHO/EU) criteria for selected water quality parameters; (ii) to characterise site-specific soundscapes and identify predominant natural and anthropogenic acoustic signatures; and (iii) to integrate these datasets in order to enhance interpretation of environmental pressures and inform localized management and communication strategies. By coupling conventional laboratory analyses with sensory and contextual information derived from soundscape data, the study aims to provide a more nuanced appraisal of river condition and to demonstrate the utility of multidimensional monitoring approaches for riverine conservation and public engagement.

MATERIAL AND METHODS

Study Sites

Field investigations were carried out in September 2024 at three representative locations along the Danube River within the urban area of Novi Sad, Serbia (Fig.1). The sites were selected to capture a gradient of anthropogenic pressures ranging from recreational to industrial activities:

- Burma Beach (NS3): A semi-recreational site located downstream of the city, frequently used for bathing and leisure activities during summer months. At the time of sampling, ongoing construction activities in the vicinity, together with episodic waste disposal, represented potential sources of localized disturbance.
- Estuary of the Danube–Tisza–Danube (DTD) Canal (NS2): Situated at the confluence of the artificial canal network with the Danube, this site is strongly influenced by navigation, shipping activities, and intensive anthropogenic inputs. Floating litter and traces of oil films were visibly present at the water surface during fieldwork.
- Resort Ribarsko Ostrvo (NS1): A popular recreational and tourist area positioned close to a major traffic bridge. This site experiences continuous acoustic disturbance from road traffic, but hydrological conditions are relatively stable due to its distance from industrial discharge points.

Together, these sites provide a useful basis for evaluating how different land-use types and anthropogenic activities affect both the chemical status and the acoustic environment of the river.

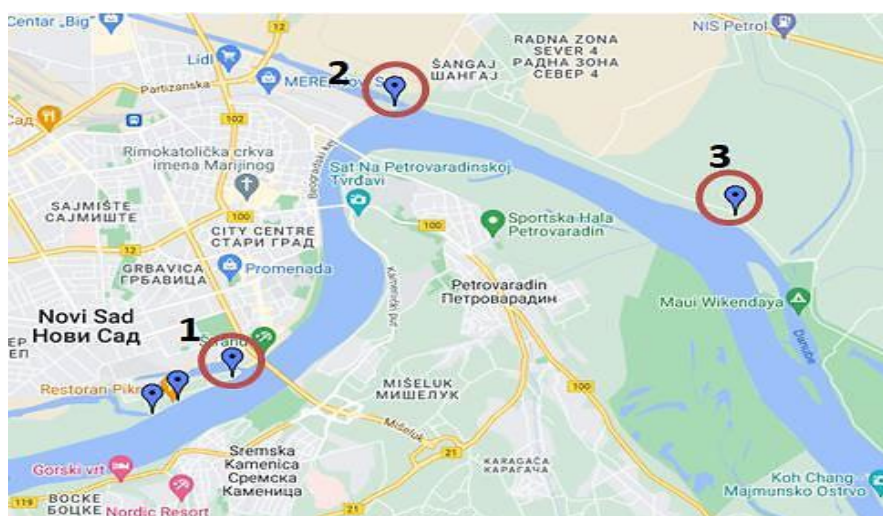


Fig. 1. Map of the sampling sites

Water Quality Analysis

Water samples were collected in pre-cleaned polyethylene bottles at a depth of approximately 0.5 m, stored under refrigerated conditions, and transported to the laboratory within 24 hours for analysis. Analytical procedures followed standard protocols defined by Serbian national regulations on surface water quality [6] and were cross-referenced with World Health Organization (WHO) drinking water guidelines [1] to ensure comparability with international standards.

The following physicochemical parameters were measured:

- Dissolved oxygen (DO): Winkler titration method;
- Biochemical oxygen demand (BOD₅): Five-day incubation at 20 °C;
- Nutrients: Nitrate (NO₃⁻), nitrite (NO₂⁻), ammonium (NH₄⁺), and total phosphorus (TP) were quantified using spectrophotometric methods after appropriate sample preparation;
- Organic load indicators: Total organic carbon (TOC) determined by high-temperature catalytic combustion;
- Heavy metals (As, Cu, Pb, Ni, Cd): Measured by inductively coupled plasma–mass spectrometry (ICP–MS) following acid digestion.

All analyses were conducted in triplicate to ensure accuracy and reproducibility. Results were evaluated against Serbian surface water quality classes (I–V) and compared with WHO recommended thresholds.

Acoustic Monitoring

To complement water quality analysis, a systematic program of acoustic monitoring was implemented at each site. Recordings were conducted using a dual-channel setup consisting of a calibrated hydrophone (sensitivity: –164 dB re 1 V/μPa, frequency response: 20 Hz–20 kHz) and an omnidirectional ambient microphone (frequency response: 20 Hz–20 kHz, positioned at 1.5 m height). Each recording session lasted 15 minutes, performed under stable meteorological and hydrological conditions to ensure comparability.

Recordings were processed using specialized software (e.g., Raven Pro, Audacity) to generate spectrograms and frequency distributions. Key acoustic parameters included:

- Sound Pressure Level (SPL, dB re 1 μPa underwater / dB(A) in air): quantifying the intensity of sound at different frequency bands.
- Frequency composition: separating low-frequency (<500 Hz, typically associated with shipping and construction) from mid-to-high frequencies (>1 kHz, often related to bird vocalizations or recreational activity).
- Temporal variability: distinguishing continuous (traffic, ship engines) from intermittent signals (bird calls, short machinery bursts).

This approach enabled both qualitative identification of dominant sound sources and quantitative assessment of their intensity and variability. By integrating these findings with water quality data, a more comprehensive picture of anthropogenic pressures on the river ecosystem was obtained.

RESULTS AND DISCUSSION

Water Quality

The overall results indicate that the Danube River in the Novi Sad region maintains a generally good ecological status, but with localized signs of anthropogenic stress (Table 1). Across all sites, concentrations of dissolved oxygen (DO) remained within Class I limits, reflecting favorable conditions for aquatic life and efficient self-purification capacity. Similarly, nitrate and nitrite levels were consistently low, suggesting that nutrient enrichment was not a dominant pressure at the time of sampling. These findings are consistent with earlier studies on the Serbian stretch of the Danube, which also reported relatively stable oxygen conditions and moderate nutrient concentrations under non-flood conditions [7,8].

However, several parameters revealed site-specific exceedances that lowered the ecological classification from Class I to Class II or III. Total organic carbon (TOC) values exceeded Class I thresholds at all three sites, highlighting the influence of urban runoff, organic discharges, and intensive human use of the river. Elevated ammonium was detected at NS3 (Burma Beach), likely linked to both untreated wastewater inputs and seasonal recreational pressures. At NS2 (Estuary DTD), concentrations of arsenic and copper exceeded Class II limits, pointing to inputs from shipping activities and industrial runoff transported via the canal system. In contrast, NS1 (Ribarsko Ostrvo) displayed relatively stable conditions, with exceedances limited to TOC. Importantly, concentrations of cadmium, nickel, and lead remained below national and WHO thresholds at all sites, indicating no acute heavy metal contamination at the time of sampling.

These localized deviations from high ecological status are consistent with broader basin-wide assessments such as the Joint Danube Survey, which has repeatedly identified urban centers and canal confluences as hotspots for organic and trace metal pollution [9].

Table 1. Results of physico-chemical analysis of Danube River water

Parameter	Unit	Determined Value			Guideline Value ¹	Thresholds ²				
		Burma Beach	Estuary DTD	Ribarsko		Class 1	Class 2	Class 3	Class 4	Class 5
Dissolved Oxygen	mg-O ₂ /L	9.2	9.7	9.9	-	>8.5	7	5	4	<4
Nitrates	mg-N/L	1.1	1.1	1.1	50 mg/L	1-1.5	3	6	15	>15
Nitrites	mg-N/L	0.014	0.026	0.008	3 mg/L	0.01	0.03	0.12	0.3	>0.3
Ammonium	mg-N/L	0.3	0.29	0.1	*Not established but natural levels usually below 0.2 mg/L	0.1 – 0.05	0.1 – 0.3	0,6	1.5	>1.5
Lead	µg/L	2.2	9.8	2.3	10 µg/L	-	-	-	-	-
Cadmium	µg/L	0.3	0.6	0.3	3 µg/L	-	-	-	-	-
Copper	µg/L	3,2	9.8	1.9	2 µg/L	5	5	500	1000	>1000
Arsenic	µg/L	2.8	6.1	1.4	10 µg/L	<5	10	50	100	>100
Total Chromium	µg/L	0.5	13.3	1.4	-	-	-	-	-	-
Total Phosphorus	mg-P/L	<0.04	<0.04	<0.04	-	0.05	0.2	0.4	1	>1
Sodium	mg/L	11.3	11.4	11	*Not established but natural levels usually below 20 mg/L	-	-	-	-	-
Biological Oxygen Demand (BOD ₅)	mg-O ₂ /L	1.5	2.5	1.3	-	1.8 – 2.0	4.5 – 5.0	7	25	>25
Potassium	mg/L	<2	2.5	2.4	-	-	-	-	-	-
Nickel	µg/L	<2	18.8	5.6	70 µg/L	-	-	-	-	-
Calcium	mg/L	48.3	48.2	48.1	-	-	-	-	-	-
Magnesium	mg/L	12.3	12.4	12.4	-	-	-	-	-	-
Total Organic Carbon TOC	mg/L	3.7	3.6	3.6	-	2	5	15	50	>50

¹ World Health Organization (WHO). (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum.

² Official Gazette of the Republic of Serbia, No. 50. (2012, May 18) – "Regulations on limit values of polluting substances in surface and underground waters and sediment and deadlines for reaching them"

Acoustic Soundscapes

Soundscape analysis revealed pronounced differences among the three study sites, reflecting both their geographical context and dominant human activities.

- NS3 (Burma Beach): Recordings captured a mixture of natural and anthropogenic sounds. Bird colonies were particularly prominent, contributing positively to the ecological acoustic signature. However, background construction noise was consistently present, and underwater recordings showed intermittent low-frequency disturbances likely linked to nearby machinery.
- NS2 (Estuary DTD): This site was dominated by anthropogenic acoustic activity. Ship engines, propeller turbulence, and radio frequency interference were the most distinctive sound sources. Such noise pollution has been reported in other navigational hotspots along the Danube [10], where it poses risks for aquatic fauna, particularly fish species sensitive to low-frequency vibrations.
- NS1 (Ribarsko Ostrvo): Above-water recordings were strongly influenced by continuous traffic noise from the adjacent bridge, overshadowing natural sound signals. In contrast, underwater recordings showed more stable soundscapes, with relatively weak anthropogenic interference. This suggests that while air-borne noise may impact human recreation and bird habitats, underwater ecosystems at this site remain less disturbed acoustically.

The integration of acoustic data provides an additional interpretative layer beyond chemical analysis. For example, NS2 showed both higher chemical stress (TOC, metals) and strong acoustic disturbance, underscoring its role as a critical pressure point. NS1, by contrast, appeared chemically stable but acoustically stressed by traffic. This highlights the importance of combining multiple monitoring approaches to fully understand ecological dynamics. Moreover, the recorded soundscapes from each Novi Sad location are publicly accessible on the official STREAM project platform (<https://stream.democratia-aqua.org>), while a visual representation of the acoustic profiles is presented in Figure 2.



Fig.2. Soundscape Danube recording

Comparative Context

The observed patterns align with findings from previous Serbian studies. Milovanović [8] identified elevated organic load and trace metals near canal confluences, particularly in urban sectors, while Liška et al. [9] documented shipping corridors as noise and contamination hotspots along the middle Danube. Recent research on river soundscapes has similarly shown that anthropogenic noise can mask biological signals and interfere with ecosystem functioning [11]. By integrating chemical and acoustic indicators, the present study provides a more nuanced understanding of localized pressures in a highly urbanized stretch of the Danube.

Implications for Monitoring and Management

The results emphasize that while the Danube near Novi Sad generally complies with high water quality standards, localized stressors—particularly organic pollution, trace metals at the canal estuary, and continuous noise inputs—require targeted management. The findings suggest three key implications:

1. Enhanced monitoring frequency at NS2, where canal inputs significantly affect water quality.
2. Mitigation of organic load through improved wastewater management and stormwater treatment in urban zones.
3. Integration of acoustic monitoring into regular environmental assessments, not only to capture ecological stress but also to raise public awareness of river soundscapes as cultural and environmental assets.

Such multidimensional monitoring aligns with EU strategies for holistic water management and could be further expanded by incorporating biological indicators (e.g., benthic invertebrates, fish surveys) in future studies.

CONCLUSIONS

This study demonstrates that the Danube River near Novi Sad maintains generally good ecological conditions, with most physicochemical parameters falling within Class I limits. Nevertheless, localized exceedances of TOC, ammonium, arsenic, and copper indicate the presence of moderate pressures, particularly at the Estuary DTD (NS2) and Burma Beach (NS3). These results are consistent with previous reports identifying canal confluences and urban zones as hotspots for organic and trace metal pollution along the Danube.

Acoustic monitoring revealed site-specific soundscapes that enriched interpretation of chemical data. While NS1 (Ribarsko Ostrvo) appeared chemically stable but acoustically affected by continuous traffic, NS2 combined both chemical stress and intensive shipping-related noise, reinforcing its role as a critical pressure zone. Such findings underscore the importance of integrating sensory dimensions into water quality assessments, as they capture environmental disturbances that may otherwise remain undetected.

Overall, the combination of physicochemical and acoustic approaches provided a multidimensional understanding of river conditions in an urbanized setting. This methodological framework can support more effective environmental monitoring, communication with stakeholders, and awareness-raising among the public. Future research should build on these findings by incorporating biological indicators and long-term monitoring to further enhance sustainable management of the Danube in Serbia.

Acknowledgements

This research has been supported by the Ministry of Science, Technological Development and Innovation through Contract No. 451-03-36/2025-03/200156, Faculty of Technical Sciences

(No.115001-3394/1), HORIZON-MSCA-2021-SE-01, Project No.101086387 (REMARKABLE), and STREAM Project, funded by Baden-Württemberg Stiftung.

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