MINISTRY OF EDUCATION AND RESEARCH
“AUREL VLAICU” UNIVERSITY OF ARAD
INTERDISCIPLINARY DOCTORAL SCHOOL
DOCTORAL FIELD: ENVIRONMENTAL ENGINEERING

DOCTORAL THESIS

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ARAD
2026

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STUDY OF THE TIMIȘ–BEGA RIVER BASIN FROM THE PERSPECTIVE OF WATER QUALITY

ABSTRACT OF THE DOCTORAL THESIS

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Chapter 1. Introduction

The study of water quality is a priority in scientific research, essential for sustainable development and the preservation of vital resources. In the context of climate change and anthropogenic pressures, the assessment of water quality has become central. The Timiș–Bega basin is characterized by hydrological and geomorphological complexity, as well as vulnerability to pollution, making it an ideal subject for comprehensive studies.

The motivation for this topic arises from the lack of integrated studies on water quality and bank morphodynamics in the Timiș–Bega basin. The topic provides applied results that can contribute to resource management strategies and erosion reduction. It aligns with European Union priorities regarding water protection, being relevant both scientifically and practically. The general aim of the research is to assess the water quality in the Timiș–Bega basin and to highlight the links between the geomorphological instability of riverbanks and aquatic pollution. The specific objectives include: characterizing water quality, identifying erosion processes, analyzing the relationship between sediment dynamics and pollutants, and formulating recommendations for integrated water management.

The hypotheses suggest that water degradation is influenced by geomorphological processes that introduce sediments and contaminants. Eroded areas represent pollution hotspots, and the integrated analysis of hydrological and geomorphological parameters provides a deeper understanding of pollutant transport.

The contributions include the creation of a database on water quality and bank dynamics, innovative methodologies for correlating these processes, and the identification of high-risk areas. These can support resource management strategies and policies for the protection of aquatic ecosystems.

Chapter 2. Theoretical Framework and State of Research

Surface water quality represents a fundamental indicator of the health status of aquatic ecosystems, and its assessment requires an integrated approach that combines physico-chemical, biological, and geomorphological parameters.

A determining factor, yet often underestimated in traditional approaches, is the morphodynamics of riverbanks. Erosion processes and slope instability not only facilitate changes in the riverbed, but also enhance sediment transport, which significantly contributes to the redistribution of contaminants—such as nutrients and heavy metals—from sediments directly into the water column. This creates a critical interdependence between fluvial geomorphology and aquatic ecology.

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In accordance with European directives, particularly the Water Framework Directive (2000/60/EC), a holistic analysis of water bodies is required, taking into account both natural and anthropogenic pressures. Although the Timiș–Bega river basin has benefited from numerous studies on hydrological regimes and water quality, the specific influence of geomorphological bank dynamics on contamination processes represents a significant gap in the national scientific literature. Exploring this dimension is essential for a comprehensive understanding of diffuse pollution phenomena in the region.

This literature review establishes the conceptual framework of the research by articulating theoretical concepts related to water quality with fluvial morphodynamic processes. By highlighting the correlations between bank stability and water contamination, as well as identifying knowledge gaps related to the Timiș–Bega basin, the study justifies its originality and demonstrates its significant contribution to the advancement of scientific knowledge in a deeply multidisciplinary field.

Fluvial morphodynamics describes changes in riverbeds through erosion, sediment transport, and deposition, influenced by natural and anthropogenic factors. These processes modify river morphology and affect both the hydrological regime and ecosystems [15,18,19].

Geomorphology, ecology, and hydrology interact through feedback mechanisms: channel form influences habitat conditions, vegetation stabilizes riverbanks, and the hydrological regime controls erosion and river evolution [21,24,27,28].

Human interventions can disrupt the natural balance, stabilizing certain areas while destabilizing others, with consequences for habitats and flood risk [24,27].

Effective river management requires an integrated approach that differentiates between areas where infrastructure protection is necessary and those where natural dynamics should be allowed. This approach involves community participation and balances economic objectives with ecosystem conservation [28].

Geomorphological processes control the mobilization and transport of sediments and pollutants, thereby amplifying ecological risks. Their management requires source stabilization, sediment control, and monitoring during critical events.

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The application of the Water Quality Index (WQI), highlighted by Dunca (2018), revealed the degradation of water quality downstream along the Timiș and Bega rivers, identifying spatial patterns and pollution sources, including transboundary issues between Romania and Serbia [41].

The study by Senilă et al. (2017) highlighted groundwater contamination with arsenic, mostly in labile form, indicating significant health risks in the analyzed communities [42].

The study by Oprean et al. (2013) established reference values for physico-chemical and microbiological parameters, identifying areas with high sanitary risk [43]. The study by Popescu et al. (2013) revealed low microbial activity in sediments and local indicators of fecal pollution [44].

Despite significant gaps, integration between surface and groundwater remains insufficient, and arsenic data are not systematically correlated with basin-level assessments [41,42]. Ecological and epidemiological evaluations are rare, although health risks are documented [42]. Discontinuous monitoring series limit the detection of long-term trends [41,42,45], and sediment quality has been underestimated until the last decade [47]. Additionally, transboundary coordination between Romania and Serbia remains deficient, despite evidence of downstream impacts [41].

Chapter 3. Assessment of the Influence of Anthropogenic Activities on Water Quality at the River Basin Level

Water quality in river basins is influenced by both natural factors (soil characteristics, seasonal variability, basin type) and anthropogenic factors, particularly human activities such as industry, agriculture, urbanization, deforestation, and wastewater discharge [49–55].

In addition to human activities, aquatic ecosystems are also affected by natural factors such as climate change, erosion, invasive species, and hydrological regimes. Since river water is used for consumption, maintaining its quality is essential, while groundwater is considered particularly vulnerable [56,57].

Meteorological changes strongly influence hydrological systems: precipitation and snowmelt increase the input of chemicals and sediments through erosion, affecting aquatic habitats. Furthermore, invasive species can disrupt ecosystems and degrade water quality.

Maintaining water quality requires conservation measures, strict regulations, and sustainable agricultural practices. According to Liu et al., expanding monitoring efforts contributes to maintaining optimal parameters [52,59]. Awareness of the impact of human activities is essential for water protection. Assessing these effects enables a better understanding of existing problems and supports the development of effective strategies for the management and conservation of water resources.

The increasing anthropogenic pressures make it essential to identify and manage sources of contaminants within catchment areas. Water quality affects both ecosystems and human health. This study aims to highlight these sources and propose strategies for reducing pollution and maintaining high-quality water resources. Figure 2 presents the main strengths and opportunities associated with water quality management in river basins, emphasizing the importance of coordinated international cooperation, technological innovation, and environmental education in protecting and conserving water resources.

This represents a valuable method of strategic synthesis, improving the interpretation of results and supporting the formulation of recommendations and policies. It is an essential tool for Integrated Water Resources Management (IWRM), widely used in numerous studies to assess the implementation of sustainability objectives [62,65–67].

The literature was selected using Google Scholar and ScienceDirect, based on general and specific keywords related to water quality and the impact of anthropogenic activities. Relevant combinations of terms regarding pollution, land use, agriculture, urbanization, mining, and wastewater were used to identify pertinent studies.

In Romania, fragmented monitoring is being addressed through investments in equipment and emergency systems under PNRR, highlighting the need for local-level support. In conclusion, although IWRM and the Water Framework Directive (2000/60/EC) provide solid frameworks, reforms, improved funding, and integrated implementation are still required to reach their full potential.

Soil water is essential for crop development but can also transport pollutants such as pesticides, nitrates, and phosphates [80]. Intensive agriculture contributes to water contamination through runoff and erosion, affecting both surface and groundwater.

Soil characteristics, climate, and topography influence the transport of contaminants, including phosphorus, heavy metals, carbon, and microplastics [81–89],[98]. Studies highlight the role of these factors and the variability of impacts depending on local conditions [83].

To reduce pollution, sustainable agricultural practices, controlled fertilization, anti-erosion measures, and integrated monitoring are required [90–91]. Agricultural activities remain a major source of diffuse pollution, requiring coherent policies to protect water resources and limit eutrophication [100].

Hydro-climatic events control the mobilization and transport of pollutants, determining whether they remain localized, are transported with sediments, or become concentrated in channels. Studies on the Timiș River highlight these mechanisms.

Chapter 4. Long-Term Evolution of Riverbank Morphodynamics and Its Effects on Water Quality in the Timiș River

Rivers are dynamic systems influenced by both natural and anthropogenic factors, while topography (slope, elevation, relief) plays an important role in controlling runoff, erosion, and pollutant transport [187–192]. It influences both water quality parameters and the mobility of hazardous substances through geochemical interactions with sediments.

Human activities and land-use changes amplify these processes, while hydraulic infrastructure alters flow regimes and nutrient cycles [189,190,193,194]. Although numerous studies highlight these effects, the role of topography is still insufficiently integrated into water quality models [197,198].

Water quality assessment relies on methods such as monitoring sections and the Water Quality Index (WQI), integrated into European environmental policies. In this context, the Timiș River represents a relevant case, affected by anthropogenic pressures and complex natural characteristics, yet insufficiently analyzed over the long term.

The proposed study analyzes water quality over an extended period, integrating natural and anthropogenic factors, in order to support the development of effective strategies for water resource management and protection, in accordance with European policies.

The Timiș Basin is located in southwestern Romania and northern Serbia, extending from the Western Carpathians to the Pannonian Basin. It is bordered by the Bega–Tisa system to the north, the Caraș and Nera basins to the east, the Danube to the south, and the Mureș and Tisa to the west. The upper sector crosses mountainous areas such as the Semenic Mountains, while the lower sector develops within an alluvial plain.

The Timiș River drains a basin of approximately 10,280 km^2 (≈7,310 km^2 in Romania), with a length of about 359 km until its confluence with the Danube near Pančevo, and an average discharge of 47 m^3/s. It flows through urban and industrial centers such as Caransebeș, Lugoj, and Pančevo, being exposed to point-source pollution. Measurements indicate chloride values up to 18.3 mg/L and sulfates up to 68.8 mg/L, associated with anthropogenic influences, while the region is affected by water stress during drought periods. Monitoring is carried out by the Banat River Basin Administration [35].

The study analyzed the Timiș – Timișana–border sector (90.21 km), using two sections: Șag (upstream urban and agricultural influences) and Grăniceri (downstream, transboundary conditions). The coordinates (Șag: 45.69°N, 21.06°E; Grăniceri: 45.55°N, 20.85°E) ensure reproducibility of the analysis.

The study of the Timiș River examined essential physico-chemical water parameters (COD-Cr, BOD_5, dissolved oxygen, conductivity, pH, nutrients, detergents, phenols, and heavy metals such as As, Cr, Cu, Zn), based on national methodologies [211]. Data were collected annually between 2013–2023 and analyzed in accredited laboratories, ensuring a comprehensive dataset for pollution assessment [212].

Topographic measurements conducted using a GNSS receiver revealed riverbank variations (~11 cm), relevant for erosion processes and pollutant retention, with differences being significant compared to measurement errors. The analyzed sections included both stable and unstable banks, in order to assess their influence on pollutant dynamics.

The results indicate that the studied sector has potential for uses such as irrigation; however, the presence of pollution sources requires treatment measures. The transboundary nature of the river also requires compliance with international legal frameworks for water resource protection.

The results were synthesized into a correlation matrix, facilitating the identification of direct and inverse relationships, as well as potential sources of pollution (organic, nutrient-related, industrial) [214]. Although the data are annual and limited in number, long-term consistency and the use of multivariate analyses provide a solid basis for trend evaluation.

Understanding the correlations between physico-chemical parameters is essential for assessing water quality and identifying pollution sources, as these relationships are influenced by both natural and anthropogenic processes [1]. The study analyzes 11-year variations for indicators such as BOD_5, COD-Cr, dissolved oxygen, nutrients, detergents, phenols, and heavy metals, tracking the relationships among them.

The results support the use of integrated, multi-indicator approaches, while annual visualizations highlight exceedances of legal limits, facilitating their correlation with environmental factors or anthropogenic activities [2–6].

Table 4 summarizes the main indicators for each of the characteristics considered in this study. Maximum values were frequently recorded in 2013, 2019, and 2023. Data distribution is negatively skewed (to the left) for BOD_5, conductivity, pH, and Zn, where the mean is lower than the median, indicating a concentration of values toward higher levels.

For $N\text{-}NH_4$ and $N\text{-}NO_2$, the distribution is approximately symmetrical, while the other parameters show positive skewness (to the right), suggesting the presence of high values that influence the mean.

Biochemical Oxygen Demand (BOD_5)

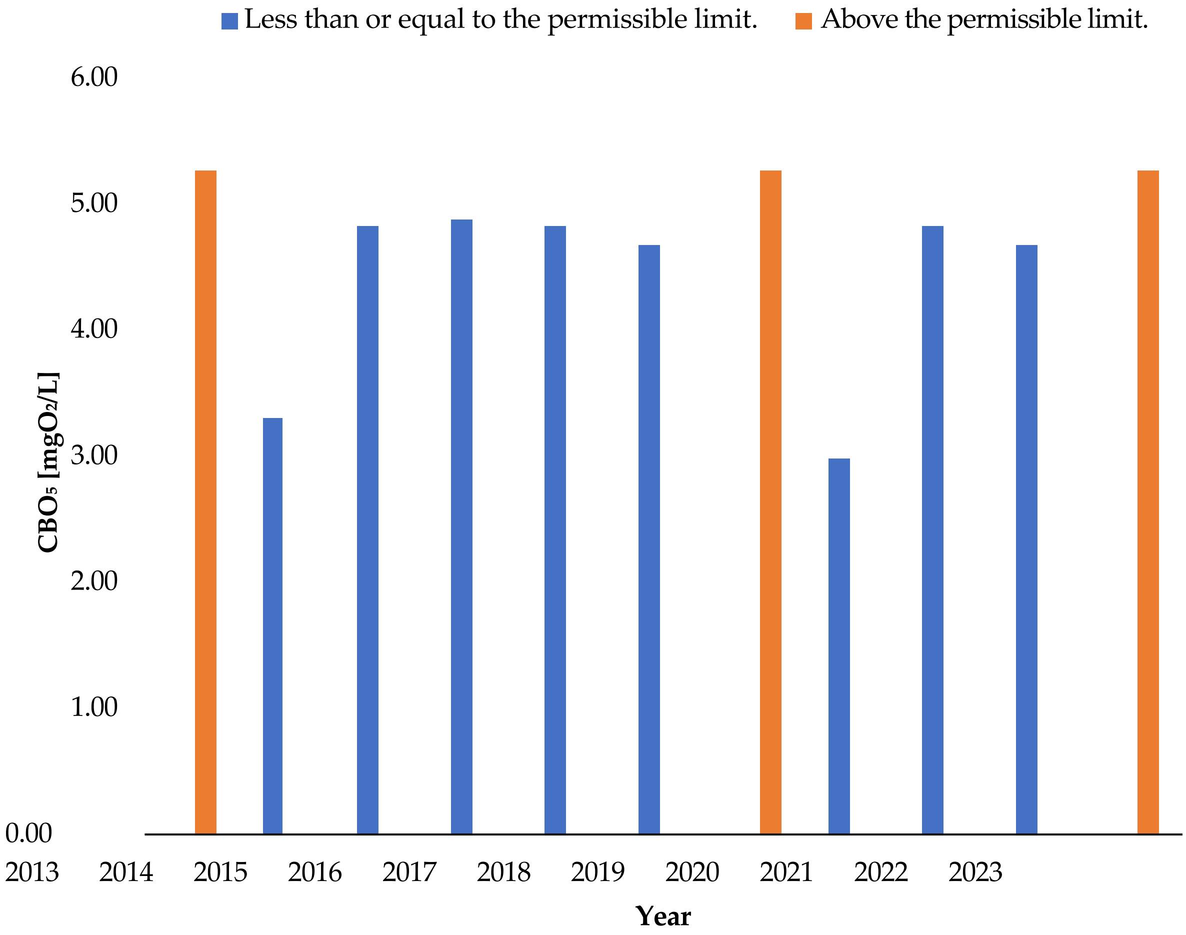

Figure 1. Evolution of the BOD_5 Parameter During the Analyzed Period

Chemical Oxygen Demand (COD-Cr)

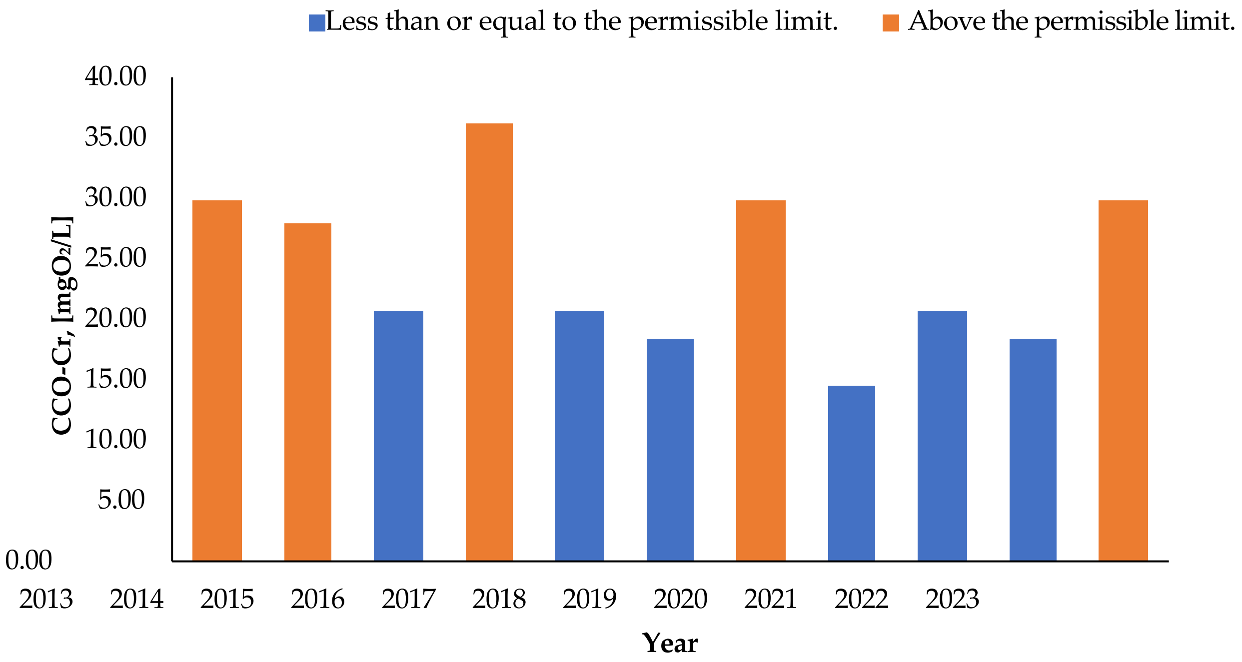

Figure 2. Evolution of the COD-Cr Parameter During the Analyzed Period

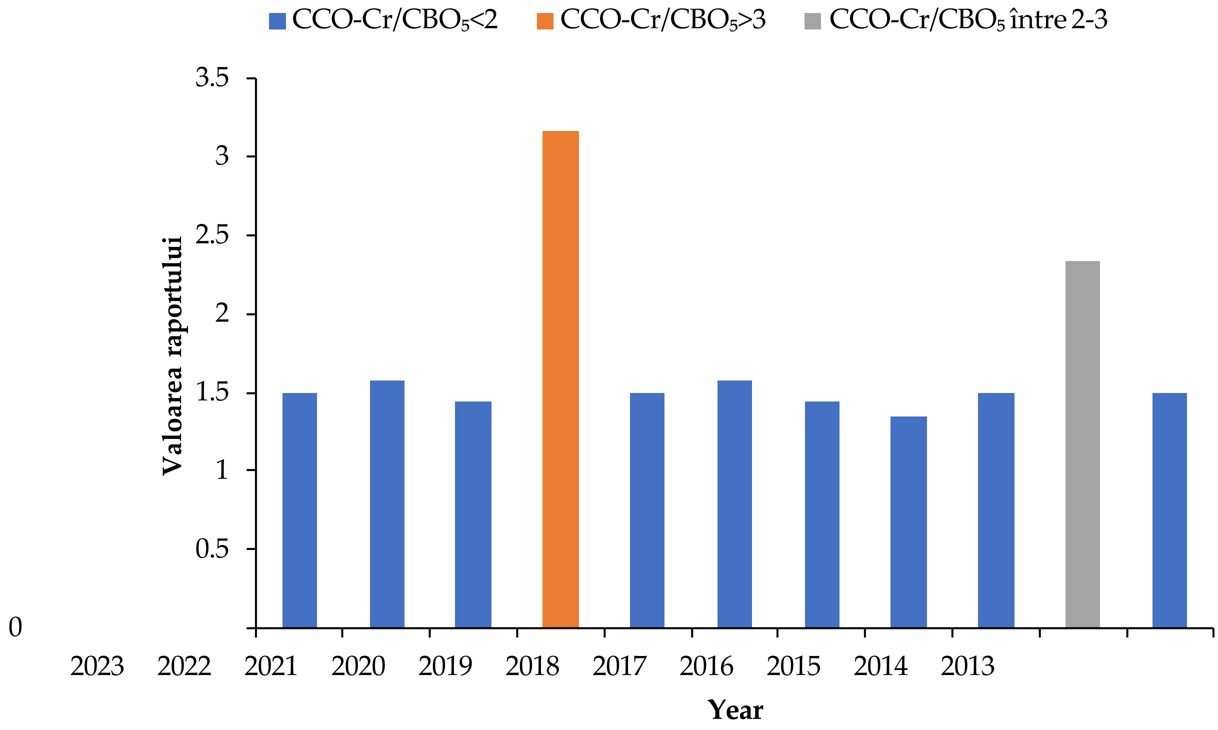

Figure 3. COD-Cr/BOD$_5$ Ratio During the Analyzed Period

Dissolved Oxygen (DO)

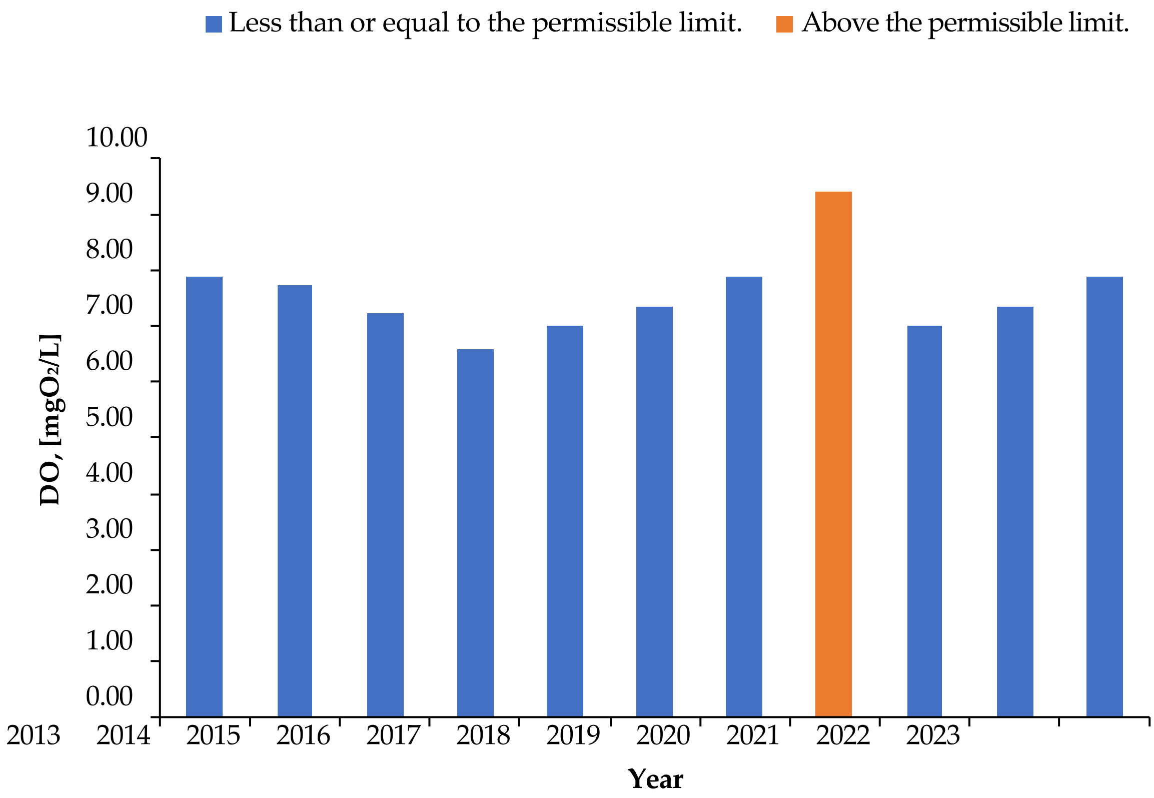

Figure . Evolution of Dissolved Oxygen During the Analyzed Period

Conductivity

Figure 5. Evolution of the Conductivity Parameter During the Analyzed Period

pH

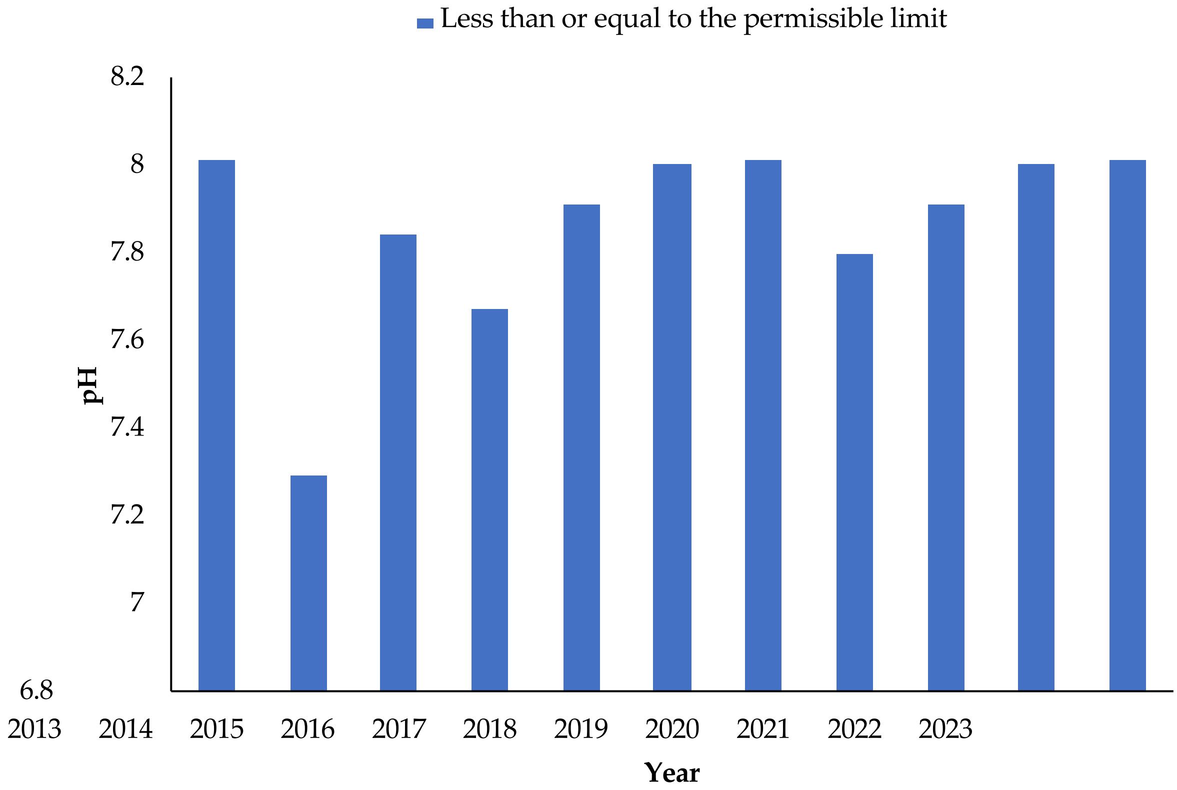

Figure 6. Evolution of the River pH Parameter During the Analyzed Period

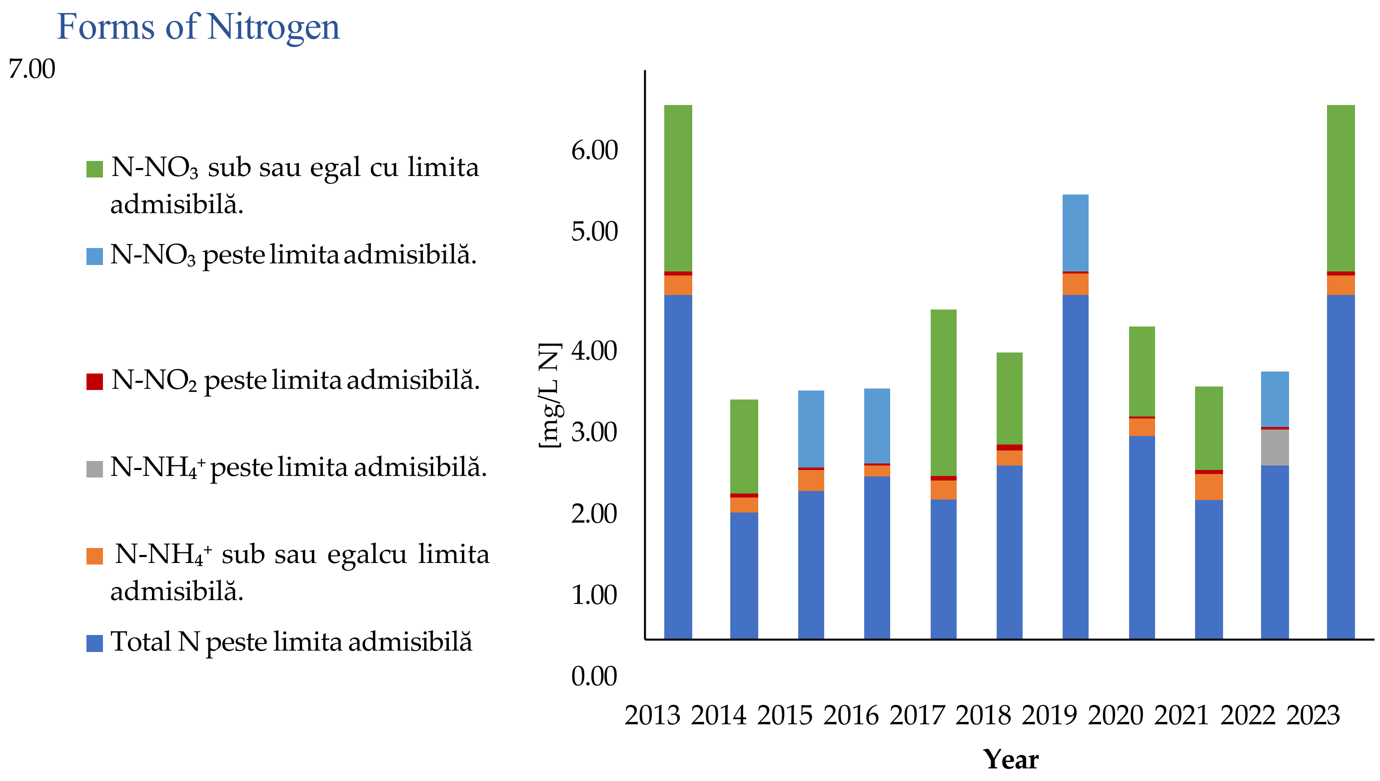

Figure 7. Evolution of Different Forms of Nitrogen in the River During the Analyzed Period

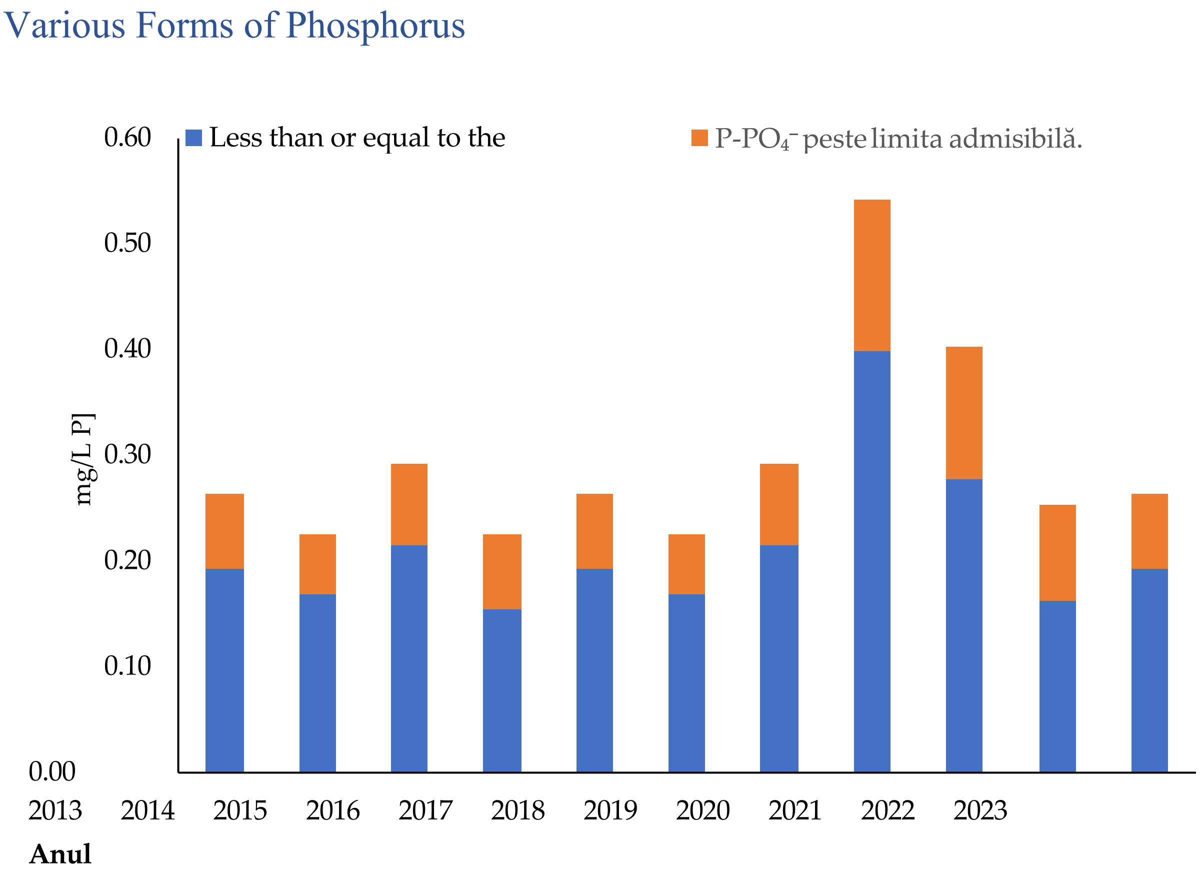

Figure 8. Evolution of Different Forms of Phosphorus in the River During the Analyzed Period

To facilitate data interpretation, water quality parameters were grouped based on their correlations, using the Pearson coefficient (r), which highlights the strength and direction of linear relationships between variables [242]. The analysis of the correlation matrix allowed the identification of relevant relationships among parameters, suggesting common pollution sources and dominant processes within the basin.

The strongest relationship identified is between total nitrogen and nitrates ($r = 0.97$), indicating that the oxidized form (NO_3^-) dominates the nitrogen balance. This situation is typical for basins influenced by agriculture, where fertilizer use leads to diffuse pollution. At the same time, nitrate dominance suggests a well-oxygenated environment, in which nitrification processes are efficient, and reduced forms (NH_4^+, NO_2^-) are limited.

A strong correlation was also observed between total phosphorus and orthophosphates ($r = 0.89$), indicating the predominance of the bioavailable form. This suggests inputs from domestic wastewater or insufficiently efficient treatment processes, particularly in the context of low levels of anionic detergents.

The correlation between zinc and COD-Cr (r = 0.79) indicates common sources, most likely of urban or domestic origin, such as wastewater, road runoff, or cosmetic products. Similarly, the relationship between BOD_5 and conductivity (r = 0.76) suggests that biodegradable organic matter and dissolved ions originate from the same sources, such as wastewater, manure infiltration, or agro-industrial activities.

On the other hand, weaker correlations provide additional insights into system balance. The modest relationship between COD-Cr and BOD_5 (r = 0.43) indicates a relatively low contribution of biodegradable organic pollution, while the weak negative correlation between dissolved oxygen and COD-Cr (r = -0.32) suggests limited oxygen consumption, confirming moderate organic pressure on the ecosystem.

Overall, the correlation analysis highlights the predominance of diffuse pollution of agricultural and domestic origin, as well as a relatively well-oxygenated system in which biochemical processes are active but without major imbalances.

The analysis of negative correlations reveals inverse relationships between water quality parameters, providing valuable insights into biogeochemical processes and pollution sources. The strongest relationship identified is between copper (Cu) and ammonium ($N\text{-}NH_4^+$), with a coefficient of -0.9. This very strong correlation suggests a possible toxic influence of copper on microbiological processes involved in the nitrogen cycle. Increasing Cu concentrations may inhibit microorganisms responsible for ammonium accumulation or transformation, indirectly favoring its conversion into oxidized forms such as nitrates, thus explaining the high contribution of NO_3^- to total nitrogen.

A moderate negative correlation (-0.61) between Cu and orthophosphates ($P\text{-}PO_4^{3-}$) indicates that areas affected by metal pollution do not necessarily coincide with those dominated by phosphorus inputs from agricultural or domestic sources. Furthermore, copper toxicity to microorganisms involved in the phosphorus cycle may reduce the mineralization of organic phosphorus and the release of phosphates into water, leading to its accumulation in less biologically available forms.

The negative relationship between dissolved oxygen (DO) and COD-Cr (-0.558) reflects a classic mechanism of water quality degradation: as the load of oxidizable substances increases, oxygen consumption intensifies, leading to a decrease in dissolved oxygen concentration. Although the correlation is moderate, it indicates a level of ecological stress that may become critical under favorable conditions, such as high temperatures or water stagnation.

Chapter 5. General Conclusions and Future Perspectives

This research analyzes the complexity of interactions between natural and anthropogenic factors that influence water quality in river basins, with a focus on the Timiș–Bega system and, in particular, the Timiș River. The results highlight that anthropogenic pressures represent the dominant factor in water quality degradation, manifested through GGGG diffuse sources (agriculture, urbanization) and point sources (industrial and municipal effluents), with cumulative effects on aquatic ecosystems.

The Timiș–Bega basin is characterized by a complex hydrological structure, with high spatial variability determined by the mountain–depression–plain transition, regional climatic influences, and significant anthropogenic interventions. Hydrological and geomorphological processes, including bank erosion, sediment transport, and discharge variability, control the mobilization and distribution of pollutants. These processes are intensified during flood events and reduced during low-flow periods, when accumulation and concentration of contaminants prevail.

The analysis of water quality over an 11-year period (2013–2023), based on physico-chemical parameters and the general pollution index (I*I), indicates a moderate but persistent level of pollution (values between 1.98 and 2.56). This stability reflects the presence of constant pollution sources, particularly nutrients and organic matter originating from agriculture and insufficiently treated wastewater. Statistical correlations revealed strong relationships between total nitrogen and nitrates, total phosphorus and orthophosphates, as well as between organic indicators and heavy metals, suggesting combined influences of agricultural, urban, and industrial pollution.

The results show that minor geomorphological changes in the riverbed do not have a significant impact on the overall level of pollution, while persistent anthropogenic pressures dominate water quality dynamics. At the same time, aquatic and riparian ecosystems within the basin provide essential ecosystem services but are affected by fragmentation, pollution, and hydromorphological changes.

The study highlights limitations related to the temporal resolution of the data and the use of linear statistical methods, emphasizing the need for more advanced approaches and more detailed datasets. In this context, emerging technologies such as GIS, IoT sensors, and artificial intelligence-based models can improve water quality monitoring and prediction.

In conclusion, effective river basin management requires an integrated and preventive approach that combines technological measures, nature-based solutions, and coherent public policies aligned with the objectives of the Water Framework Directive (2000/60/EC). The success of these strategies depends on the active involvement of stakeholders, adaptation to local conditions, and the integration of ecological, social, and climate dimensions to ensure the long-term sustainability of water resources.

Chapter 6. Recommendations for the Implementation of Future Solutions

1. Monitoring and Digital Tools

Effective water quality management in river basins requires the integration of modern monitoring tools, advanced technological solutions, and nature-based approaches, complemented by coherent policies and active community involvement. In this regard, continuous monitoring can be significantly improved through the use of IoT-based multiparameter sensor networks, which enable real-time data collection and automatic alert transmission when critical thresholds are exceeded. The integration of GIS technologies and remote sensing facilitates the mapping of pollution sources and their correlation with land-use patterns, while artificial intelligence algorithms, such as Random Forest, XGBoost, or neural networks, enable the modeling of complex relationships between parameters and the prediction of water quality evolution. Open-data platforms and visualization tools further enhance transparency and encourage local community engagement in the monitoring process.

2. Infrastructure and Technological Solutions

From an infrastructural perspective, upgrading wastewater treatment plants by introducing tertiary treatment stages is essential for removing nutrients and emerging pollutants, including microplastics and pharmaceutical residues. In urban environments, the implementation of green infrastructure—such as green roofs, permeable surfaces, and retention basins—contributes to stormwater management and reduces pressure on sewer systems. At the same time, innovative technologies such as micro-nanobubbles, algae-based bioreactors, and bacterial bioremediation processes provide effective solutions for reducing nutrient and heavy metal loads. For rural areas, decentralized wastewater treatment systems represent a viable alternative, reducing pressure on centralized infrastructure.

3. Nature-Based Solutions (NBS)

Nature-based solutions play a fundamental role by leveraging natural ecological processes to improve water quality. Vegetated buffer zones along rivers help filter nutrients and sediments originating from agriculture, while natural or constructed wetlands function as efficient biological treatment systems and biodiversity support habitats. The restoration of floodplains and meanders enhances the self-purification capacity of rivers and reduces the impact of extreme events, while afforestation of catchment areas limits erosion and promotes nutrient retention.

4. Institutional and Policy Framework

These measures must be supported by a strong institutional framework, based on the rigorous implementation of the Water Framework Directive (2000/60/EC) and national legislation. Stricter regulation of diffuse pollution sources, particularly from agriculture, is necessary through the promotion of sustainable practices and the introduction of economic mechanisms such as payments for ecosystem services. In transboundary basins, cooperation between countries becomes essential for harmonizing monitoring systems and implementing protection measures.

5. Education and Community Engagement

Education and community involvement are central components of effective water governance. Awareness campaigns, educational programs, and citizen science initiatives can contribute to developing a “water culture” and increasing user responsibility. At the same time, public–private partnerships can support the financing of green infrastructure and ecological restoration projects.

6. Climate Change Adaptation

In the context of climate change, integrating climate risks into river basin management plans is essential. Early warning systems for floods and droughts, together with measures to enhance ecosystem resilience—such as wetland restoration and maintaining ecological connectivity—can reduce the vulnerability of aquatic systems. Thus, an integrated approach that combines technology, nature, and participatory governance represents the key to the sustainable protection of water resources.

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