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GLOBAL CHALLENGES CONCERNING WATER RESOURCES AND THEIR MANAGEMENT: CASE STUDY - THE DANUBE

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Abstract

This paper analyses the impact of global factors on the availability and quality of water resources, highlighting the need for sustainable management. In the context of climate change, population growth and intensification of economic activities, water resources are subject to significant pressures, such as pollution, overexploitation and unequal distribution. The study uses a narrative review, based on bibliographical-analytical research, comparative analysis and a case study of the Danube River Basin. The case study illustrates the complexity of managing a transboundary resource, affected by upstream pollution, hydrological variations and multiple uses. European policies and integrated management strategies applied to protect water quality and its sustainable use are analysed. The results highlight the importance of international cooperation, infrastructure modernization and the implementation of innovative solutions. In conclusion, efficient management of water resources is an essential condition for sustainable development and the prevention of future water crises.

Key words: *Danube, management, resources, sustainability, water.*

INTRODUCTION

Water is one of the most important natural resources on the planet, indispensable for the existence of life and for the functioning of modern economies. Recent European assessments show that water bodies remain under significant pressure from agriculture, pollution and climate change, while drought and flood risks are expected to intensify in the coming decades (European Environment Agency, 2024).

In Europe, the Danube River represents one of the most complex examples of transboundary water management. The Danube River Basin covers approximately 800,000 km² and includes territories from 19 European countries, making it one of the most international river basins in the world. Recent studies indicate shifts towards wetter winters, drier summers and increased high-flow and low-flow risks, which directly affect water-resource availability in the basin (ICPDR, 2021; Probst & Mauser, 2023; Pekárová et al., 2023).

The aim of this paper is to analyse the impact of global factors on the availability and quality of water resources and to highlight how European policies and integrated management strategies contribute to the protection and sustainable use of water resources.

Recent Danube-specific assessments also underline the growing importance of emerging pollutants, including PFAS, and the need for coordinated responses across the basin (Liu et al., 2025; European Commission, 2026).

MATERIALS AND METHODS

This paper is a narrative review supported by bibliographical-analytical research, comparative analysis and a Danube case study.

Literature search strategy. Sources were identified in ScienceDirect, Scopus, Web of Science and Google Scholar, together with

official documents from the European Commission, the European Environment Agency and the ICPDR. The search covered the period 2000-2026, with priority given to 2019-2026 publications on climate change, water scarcity, nutrient pollution, PFAS, microplastics and transboundary river-basin management.

Selection criteria. The search terms used were "Danube River Basin", "water management", "climate change", "nutrient pollution", "PFAS", "microplastics", "flood risk", "drought risk" and "transboundary river basin", combined with Boolean operators. Included sources were peer-reviewed articles, technical reports and official strategies in English or Romanian that addressed basin-scale hydrology, pollution, governance or management. Duplicates, opinion pieces without clear evidence base and records unrelated to basin-scale water management were excluded.

Comparative analysis. The selected publications and official documents were compared in terms of source of pressure, management response, policy instrument and expected environmental outcome.

Case study

The Danube River was analysed as a representative case study for the management of a complex transboundary resource. The following were evaluated: anthropogenic pressures on water, pollution from upstream, hydrological variations, multiple uses of the resource and management measures implemented at regional level.

Overall, more than 25 scientific papers and technical reports were synthesised through tables, graphic representations and descriptive interpretation of hydrological and water-quality indicators, with emphasis on the relationships between climatic, economic and social drivers.

RESULTS AND DISCUSSIONS

1. Global factors influencing water resources

The synthesis of the reviewed literature confirms that water resources are being reshaped by a combination of climatic, demographic and economic pressures. Climate change remains the most pervasive driver because it alters the timing, intensity and spatial distribution of precipitation, increases evapotranspiration and amplifies the frequency of compound extremes. In river basins such as the Danube, these changes translate into wetter winters, longer dry spells in summer, more erratic flow regimes and higher uncertainty for water allocation, flood protection and ecological continuity (Probst & Mauser, 2023; Pekárová et al., 2023). The practical implication is that historical hydrological averages are becoming less reliable for planning, particularly for multi-country basins where upstream and downstream conditions are tightly coupled.

Beyond climate forcing, land-use change and population growth increase the pressure on both surface water and groundwater. Urban expansion concentrates demand, increases impervious surfaces and accelerates stormwater runoff, while industrial growth raises the risk of point-source contamination through incomplete treatment and accidental releases. Agriculture exerts a dual pressure: it is the largest user of water in many European catchments and simultaneously one of the main sources of diffuse pollution through nitrates, phosphorus, pesticides and suspended solids. The European Environment Agency has repeatedly identified agriculture as a dominant pressure on European waters, and this is consistent with the Danube Basin, where nutrient enrichment remains a persistent management challenge (European Environment Agency, 2024).

Table 1 illustrates that the pressures affecting water resources are not isolated.

Table 1. Synthesis of major global drivers, dominant pressures and basin-scale implications

Driver	Typical pressure pathway	Main hydrological or ecological effect	Management implication
Climate change	Altered precipitation, higher evaporation, longer dry periods	More frequent floods and droughts; lower predictability of river discharge	Scenario-based planning, drought preparedness and flood-risk adaptation
Urbanization	Impervious surfaces, wastewater generation, storm runoff	Flash floods, sewage overloads, urban contamination	Modern sewerage, retention systems and advanced treatment
Industrialization	Effluents, accidental releases, legacy deposits	Local hotspots, persistent contamination, sediment risk	Strict permitting, monitoring and emergency response
Agriculture	Fertilizers, pesticides,	Eutrophication, nitrate loading,	Nutrient management,

Driver	Typical pressure pathway	Main hydrological or ecological effect	Management implication
	irrigation abstraction, manure	groundwater stress	precision farming and riparian buffers
Emerging pollutants	PFAS, microplastics, pharmaceuticals	Low-concentration chronic contamination	Targeted monitoring and treatment upgrades

In practice, a single basin may experience simultaneous climate stress, diffuse agricultural pollution and industrial legacy burdens. This convergence increases the probability of threshold effects, in which ecological degradation becomes visible only after the system has already lost resilience. For the Danube, this means that management should be designed as an integrated risk-reduction framework rather than as a set of sector-specific interventions.

2. Sustainable management of water resources

The literature reviewed in this study supports the view that sustainable water management must be understood as an adaptive governance process rather than as a static set of technical measures. The Water Framework Directive established a basin-oriented logic by requiring planning at the level of river basin districts, monitoring of ecological and chemical status, and coordinated action across administrative boundaries (European Commission, 2000). This approach remains highly relevant because it links environmental objectives with the use of water for drinking supply, agriculture, navigation, industry, recreation and ecosystem protection.

In the Danube context, governance is especially complex because the basin extends across a large number of countries with different economic capacities, monitoring systems and policy priorities. The Danube River Basin Management Plan and the work of the International Commission for the Protection of the Danube River provide the institutional backbone for coordination, data sharing and joint action (ICPDR, 2021). However, the review shows that good formal coordination is not sufficient by itself. Effective management also depends on implementation capacity, financing, infrastructure quality, real-time monitoring and the ability to respond to transboundary incidents before they spread downstream.

The analysis further indicates that the most robust management strategies combine regulatory instruments with technical modernization. Wastewater treatment upgrades, nutrient reduction at source, hydromorphological restoration, floodplain reconnection and digital monitoring platforms are complementary rather than competing measures. This is important because point-source control alone cannot address diffuse pollution, and river restoration alone cannot compensate for persistent chemical loading. The strongest results are obtained when policy instruments are aligned with ecological processes and when each intervention targets a clearly defined pressure-response pathway.

Table 2 highlights that resilience depends on the combination of measures rather than on a single dominant solution. Digitalization improves detection and forecasting, but it does not remove pollution sources. Likewise, structural measures such as treatment plants or embankments improve control, but they do not replace basin-wide cooperation. A sustainable framework therefore requires a layered approach that combines prevention, monitoring, restoration and adaptation.

Table 2. Policy and technical responses for improving water resilience in the Danube Basin

Response category	Operational focus	Expected outcome	Implementation challenge
River-basin planning	Coordinated targets for water quantity and quality	Reduced conflict between users	Different national priorities
Monitoring and early warning	Dense sampling and digital alert systems	Faster detection of pollution or hydrological stress	Data harmonization across borders
Wastewater modernization	Collection, secondary and advanced treatment	Lower nutrient and micropollutant loads	High capital and operating costs
Agricultural best practice	Precision fertilization and buffer strips	Reduced diffuse runoff	Adoption at farm level
Nature-based solutions	Wetland restoration and floodplain reconnection	Improved retention and ecosystem services	Land availability and governance

3. Case study - the Danube

The Danube is a particularly instructive case because it concentrates almost all of the management challenges discussed above. It is

one of Europe's largest transboundary rivers, links highly urbanized, industrial and agricultural zones, and ultimately delivers water and sediment to the Black Sea. Its basin-scale significance means that local disturbances are rarely local for long: pollutants, hydrological changes and land-use pressures can propagate over long distances and across national borders.

The case-study evidence indicates that the river is exposed to three interacting pressure fields. First, climatic variability affects seasonal discharge, water temperature and the occurrence of low-flow or flood events. Second, point-source pollution from urban wastewater, industrial discharges and accidental releases can create acute contamination hotspots. Third, diffuse pollution from agriculture and urban runoff contributes chronic nutrient and chemical loading, which is often more difficult to reduce because it arises from many distributed sources rather than a single discharge point.

The Danube's historical pollution events demonstrate the basin-wide consequences of upstream incidents. The Baia Mare cyanide spill and the Baia Borşa tailings release remain emblematic examples of how mining accidents can create severe downstream ecological damage with long recovery times (ICPDR, 2000). Likewise, the Ajka red-sludge accident showed that industrial failures in one part of the basin can trigger water-quality emergencies hundreds of kilometres away. These cases are not merely historical references; they reveal structural vulnerabilities in basin governance, especially where prevention, emergency communication and remediation are uneven across borders.

At the same time, the review shows that the Danube cannot be interpreted only through spectacular accident cases. The dominant long-term burden is diffuse nutrient transport. Model-based work has repeatedly found that agricultural and mixed diffuse sources are the principal contributors to nutrient loading, while point sources and legacy hotspots require targeted local control (Malagó et al., 2015; 2017). This pattern matters because chronic eutrophication and sediment contamination produce slow but cumulative ecological damage, including altered food webs, reduced oxygen availability and increased pressure on biodiversity.

The emerging PFAS evidence strengthens this interpretation. The 2025 Upper Danube Basin study reported contamination across environmental compartments and highlighted the combined role of industrial hot spots, wastewater pathways and groundwater-linked transport (Liu et al., 2025). The European Commission's 2026 assessment reinforced the same message by showing that PFAS pollution in the basin is widespread and that conventional wastewater treatment is often insufficient to stop downstream dispersal (European Commission, 2026). Taken together, these findings suggest that the Danube is entering a new phase of chemical-risk governance in which the challenge is not only to reduce a few legacy pollutants but also to manage complex mixtures of persistent, mobile and partly unregulated substances.

The discussion also points to the importance of hydromorphological pressures. Bank erosion, river training works, damming and navigation infrastructure alter sediment transport, connectivity and habitat structure. Although such interventions can support navigation, flood control or energy production, they may also reduce ecological continuity and fragment habitats. In a large basin such as the Danube, hydromorphological alteration is particularly significant because it interacts with climate-driven flow variability: where water levels are already more variable, rigid channelization can further reduce ecological buffering capacity.

From a management perspective, the Danube case study shows that resilience should be assessed at multiple scales. Local measures such as upgrading a wastewater plant may improve water quality in the immediate area, but basin-level resilience depends on whether upstream activities are also controlled. Similarly, flood-protection works can reduce immediate hazard exposure, yet if they are not integrated with floodplain restoration and ecological connectivity, they may transfer risk downstream or accelerate habitat loss. This is why the ICPDR framework remains central: it provides the institutional platform for translating scientific evidence into coordinated basin action (ICPDR, 2021).

Another important result is the growing role of monitoring technologies. Traditional periodic sampling is no longer sufficient for a river basin

of the Danube's scale and complexity. The literature increasingly supports hybrid systems that combine laboratory measurements, automatic stations, remote sensing, model-based forecasting and digital alerts. Such systems are particularly useful for drought forecasting, flood preparedness and early detection of contamination peaks. They also improve transparency, because data can be shared among riparian states more quickly and used to support joint decision-making.

Overall, the Danube demonstrates that transboundary water management is not only a matter of environmental protection but also of economic stability and social resilience. Navigation, hydropower, tourism, drinking water supply, fisheries and ecosystem services all depend on the same river system. Therefore, every major management decision involves trade-offs. The central finding of this study is that the best outcomes are achieved when governance tools, infrastructure investments and ecological restoration are treated as a single integrated policy package rather than as separate sectoral agendas.

4. Integrated discussion and implications

The synthesis of the reviewed literature and the Danube case study led to three broader implications. First, water scarcity and water pollution should be analyzed together, because they are often produced by the same pressures and they reinforce each other. For example, drought conditions concentrate pollutants, while polluted water reduces the amount of water that can be safely used for supply or irrigation. Second, basin-scale resilience depends on prevention more than on reaction: once pollutants move downstream or groundwater is contaminated, remediation becomes slower, more expensive and often incomplete. Third, innovation is most effective when it is paired with strong institutions; digital tools, for instance, cannot substitute for cross-border cooperation, but they can make such cooperation timelier and evidence-based.

In practical terms, the Danube Basin would benefit from four priorities. The first is a stronger control of diffuse agricultural inputs, especially through nutrient budgeting, precision fertilization, buffer strips and stricter manure management. The second is wastewater modernization, including the gradual deployment of advanced treatment where micropollutants and PFAS are relevant. The third is restoration-oriented river management, because wetlands and floodplains can attenuate floods, improve water retention and support biodiversity. The fourth is basin-wide digital monitoring, which would allow authorities to identify trends earlier and respond more quickly to incidents.

These priorities are consistent with the growing European emphasis on water resilience. Recent official assessments stress that Europe's waters remain under intense pressure and that climate-related extremes are likely to become more disruptive in the coming decades (European Environment Agency, 2024). Accordingly, the Danube should be viewed not only as a regional case study, but also as a model system for testing integrated adaptation, advanced pollution control and cooperative governance in a large, shared river basin.

CONCLUSIONS

Water resources in the Danube Basin are under increasing pressure from climate change, urbanization, industrialization and intensive agriculture. The review shows that diffuse agricultural pollution is the dominant nutrient source, while urban wastewater and industrial discharges remain significant point pressures.

The Danube case study highlights specific priority hotspots and hazards, including the historical mining accidents at Baia Mare and Baia Borșa, the Ajka red-sludge accident, and the emerging PFAS contamination detected in the Upper Danube Basin. These findings confirm that upstream events can have basin-wide and long-term effects.

The management response should focus on stronger transboundary cooperation, modernized wastewater and monitoring infrastructure, better control of agricultural inputs, and faster deployment of digital tools for forecasting and pollution detection. These measures are essential for improving resilience to droughts, floods and emerging pollutants in the Danube Basin.

The Danube can serve as a European model of adaptive and integrated water management only if policy, science and implementation remain aligned.

The review also indicates that emerging pollutants have moved from a marginal topic to a central one in water governance. PFAS are of particular concern because they are extremely persistent, mobile in aquatic environments and difficult to remove using conventional treatment. Recent basin-scale evidence from the Upper Danube Basin shows widespread PFAS occurrence across rivers, groundwater, wastewater and landfill-related pathways, confirming that legacy contamination and current industrial inputs can overlap within the same catchment (Liu et al., 2025; European Commission, 2026). Accordingly, the management of water quality can no longer focus solely on conventional indicators such as nutrients and oxygen demand; it must also address chemical mixtures, chronic low-level exposure and long-range transport.

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USE OF GENERATIVE ARTIFICIAL INTELLIGENCE (GenAI)

The authors declare the use of Generative Artificial Intelligence (GenAI) tools in the preparation of this manuscript. GenAI was used exclusively for language editing and text refinement in the Introduction and Conclusions sections. All scientific content, data analysis, and interpretations were developed and verified by the authors.

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