MANAGEMENT AND TECHNOLOGY SESSION

ASSESSMENT OF WASTEWATER TREATMENT, WATER QUALITY, AND CLIMATIC STRESSORS ON FRESHWATER RESOURCES IN THE EUROPEAN UNION COMPARED TO SERBIA: TRENDS AND IMPLICATIONS

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Abstract:

The sustainable management of water resources remains critical to environmental protection, public health, and ecological stability within the European Union (EU). This study evaluates recent EU progress regarding wastewater treatment infrastructure, analyses water quality indicators including organic pollutants, nitrates, and phosphates, and examines climate-induced pressures, particularly drought events, affecting freshwater availability. Our assessment is based on statistical analyses from Eurostat and the European Environment Agency (EEA).

Results demonstrate improvements in wastewater treatment connectivity, with EU average connections to secondary treatment systems rising significantly from 72.6 % in 2006 to 80.9 % in 2021. However, despite advances, water quality challenges persist, notably eutrophication driven by stable nitrate levels in groundwater (averaging 20.5 mg/l in 2021) and increasing phosphate concentrations in rivers (up by 21.3 % since 2016). Concurrently, climatic impacts, especially drought events, have exacerbated water stress, significantly affecting about 29 % of the EU territory periodically. Comparative data from Serbia reveals similar challenges but underscores significant gaps in wastewater treatment coverage and water quality, highlighting the importance of strategic regional and EU-wide water governance measures. Effective policy implementation and investment in sustainable water infrastructure are essential to counteract environmental degradation and ensure long-term freshwater security.

Keywords:

Wastewater Treatment, Water Quality, Eutrophication, Climate Change, Water Scarcity.

INTRODUCTION

The sustainable management of freshwater resources is crucial for environmental conservation, safeguarding public health, and ensuring long-term economic sustainability within the European Union (EU). Freshwater systems provide essential ecological services, support biodiversity, and underpin human activities ranging from agriculture to industry [1], [2], [3], [4]. However, these resources face mounting pressures from both anthropogenic activities and changing climatic conditions. Sustainable Development Goal 6 (SDG 6) explicitly emphasizes the necessity to guarantee the availability and sustainable management of water and sanitation for all, aligning closely with existing EU environmental frameworks such as the Water Framework Directive, the Urban Waste Water Treatment Directive, and related environmental policies designed to protect water quality and availability [2].

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In recent decades, the EU has significantly advanced its policy efforts aimed at improving water resource management [5]. Despite these efforts, persistent and emerging threats, notably water pollution from organic and nutrient contaminants, continue to challenge environmental and public health goals. Nutrient pollutants, including nitrates and phosphates, primarily originating from agricultural runoff and inadequately treated wastewater, have intensified eutrophication, leading to the degradation of aquatic ecosystems. These challenges are further exacerbated by the accelerating impacts of climate change, mainly the increasing frequency and severity of drought conditions, which strain freshwater availability and quality [3], [4], [6], [7].

Additionally, a comparative perspective, such as that involving non-EU countries like Serbia, reveals both shared environmental issues and distinct regional disparities in water infrastructure and management effectiveness. Serbia and other countries in the region demonstrate significant gaps in wastewater treatment coverage and persistent water quality challenges, which underscore the necessity for targeted, strategic policy responses, investment in infrastructure, and regional cooperation to address transboundary water management challenges [5], [7].

Given these contexts, this paper evaluates EU progress and shortcomings regarding wastewater treatment, investigates current water quality trends focusing on key pollutants such as organic matter, nitrates, and phosphates, and explores the increasing climatic pressures that exacerbate water scarcity issues. The assessment draws insights from comprehensive statistical analyses to inform strategic recommendations for policy enhancement, sustainable infrastructure investments, and cross-border cooperation to secure freshwater resources sustainably into the future.

2. METHODOLOGICAL FRAMEWORK FOR EVALUATING WATER MANAGEMENT AND QUALITY

The methodology utilized in this paper involves a detailed analysis of comprehensive statistical datasets primarily provided by Eurostat and the European Environment Agency (EEA), known for their reliability and extensive coverage of environmental and sustainability data within the EU context. Several critical environmental indicators were carefully selected to provide a robust evaluation of water management effectiveness across the EU. The indicators include wastewater treatment connectivity, specifically the percentage of populations served by secondary or advanced wastewater treatment systems, reflecting infrastructure capability and policy implementation effectiveness.

The analysis of comprehensive statistical datasets provided by Eurostat and the European Environment Agency forms served as the foundation of this research. Critical environmental indicators have been selected to evaluate the effectiveness of water management across the EU. Wastewater treatment connectivity, measured by the percentage of populations served by secondary or advanced treatment systems, was a key metric for assessing infrastructure capabilities and policy implementation. Higher connectivity rates are often linked to improved public health outcomes and reduced environmental risks, demonstrating the importance of robust wastewater management systems [8], [9].

Water quality assessment incorporates biochemical oxygen demand (BOD) alongside nitrate and phosphate concentrations. BOD levels indicate organic pollutant presence and reflect the operational efficiency of wastewater treatment facilities. Nitrate and phosphate measurements provide insights into nutrient pollution, which significantly contributes to eutrophication. Agricultural runoff, industrial discharges, and urban wastewater management practices influence these parameters, highlighting the complexity of maintaining water quality standards. Understanding the interactions between these factors is essential for addressing pollution sources and improving environmental protection strategies [10], [11], [12], [13].

Historical datasets covering the period from 2000 to 2021 facilitate the identification of long-term trends and variations in water quality and availability. Evaluating the impact of major policy directives, such as the Urban Waste Water Treatment Directive, helps track infrastructure advancements and their effectiveness in mitigating pollution. Longitudinal trend analyses and comparative benchmarking across EU member states reveal notable regional disparities [14]. Differences in wastewater treatment implementation across countries underscore the varying degrees of success in policy enforcement and infrastructure development.

Comparing these findings with data from Serbia highlights additional challenges outside the EU framework. Lower connectivity rates to advanced wastewater treatment and elevated nutrient loads in Serbian water bodies illustrate gaps in infrastructure and policy implementation. Economic constraints, regulatory differences, and geographical factors influence these variations, emphasizing the necessity of regional cooperation in addressing water management challenges [2].

Climatic stressors, such as droughts and water scarcity, further affect freshwater resource availability. Temperature fluctuations and changing precipitation patterns contribute to regional disparities in water supply and demand, complicating efforts to maintain sustainable water management. Integrating statistical evaluations with engineering and environmental analyses allows for a deeper understanding of the interactions among infrastructure, pollution control, and climate-related challenges. The combined examination of these factors provides a structured basis for assessing the effectiveness of water resource management across different regions [8], [11].

3. EVALUATION OF WASTEWATER TREATMENT, WATER QUALITY TRENDS, AND CLIMATIC IMPACTS

Evaluation of wastewater treatment, water quality trends, and climatic impact is a multifaceted subject that requires an integrated analytical approach combining environmental engineering, hydrology, and climate science. Wastewater treatment efficacy is fundamental to public health and environmental sustainability, as it directly influences the levels of organic and inorganic contaminants discharged into water bodies. Advanced treatment processes, particularly secondary and tertiary treatments, are critical in reducing biochemical oxygen demand and controlling nutrient levels, specifically nitrates and phosphates, which if unmitigated, lead to eutrophication and deterioration of aquatic ecosystems [9], [12], [13]. Concurrently, long-term water quality trends, derived from robust statistical analyses of historical datasets from sources such as Eurostat and the European Environment Agency, provide insight into the temporal dynamics of these contaminants. These trends reveal the effectiveness of existing wastewater treatment infrastructures and highlight the need for continuous upgrades and policy interventions.

Climatic impacts further complicate this scenario by altering hydrological cycles and exacerbating water scarcity and quality issues. Shifts in temperature, precipitation patterns, and the frequency of extreme weather events, attributable to climate change, affect the dilution, dispersion, and concentration of pollutants in aquatic systems. Consequently, climatic variability not only stresses current water treatment capacities but also influences the performance of these systems over time, necessitating adaptive management strategies. Integration of climatic data with water quality monitoring facilitates a comprehensive understanding of how these external stressors interact with anthropogenic pressures, ultimately informing sustainable water resource management. This integrated evaluation underscores the imperative for a coordinated approach in upgrading wastewater treatment facilities, reducing waste generation and implementing climate resilience measures to ensure both environmental protection and public health in an era of rapidly changing global conditions [15], [16], [17].

The analysis indicates significant EU-wide progress in wastewater treatment infrastructure, with connectivity to secondary treatment facilities improving from 72.6 % in 2006 to 80.9 % in 2021. This marked improvement highlights the effectiveness of EU policy initiatives, particularly the Urban Waste Water Treatment Directive, which has mandated enhanced treatment standards. Despite these infrastructural advancements, critical water quality issues persist, especially concerning nutrient pollution or waste generation, in the EU and neighbouring countries as well [15], [16].

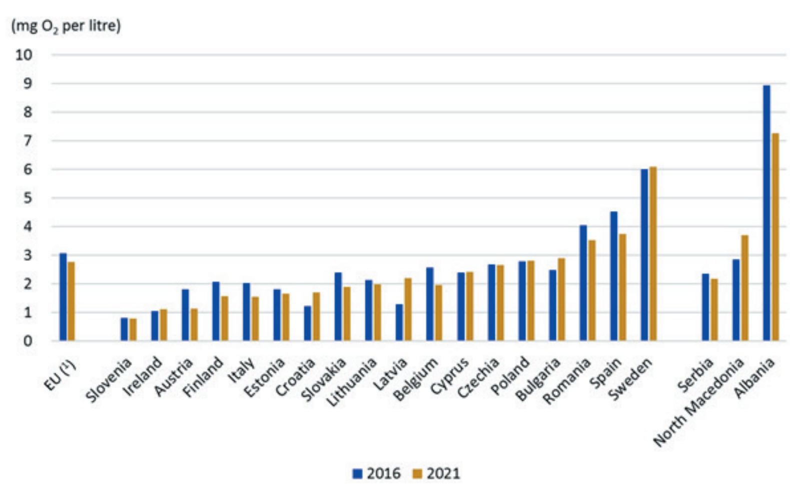

Figure 1. Biochemical oxygen demand in rivers, by country, 2016 and 2021 (mg O_2 per litre) [18]. (Fig. 6 in [18])

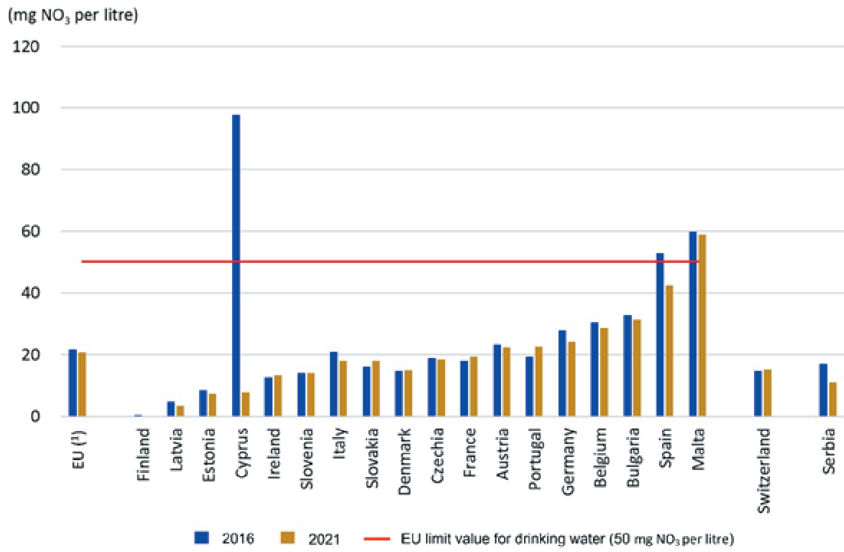

Figure 2. Nitrate in groundwater, by country, 2016 and 2021 (mg NO_3 per litre) [18]. (Fig. 8 in [18])

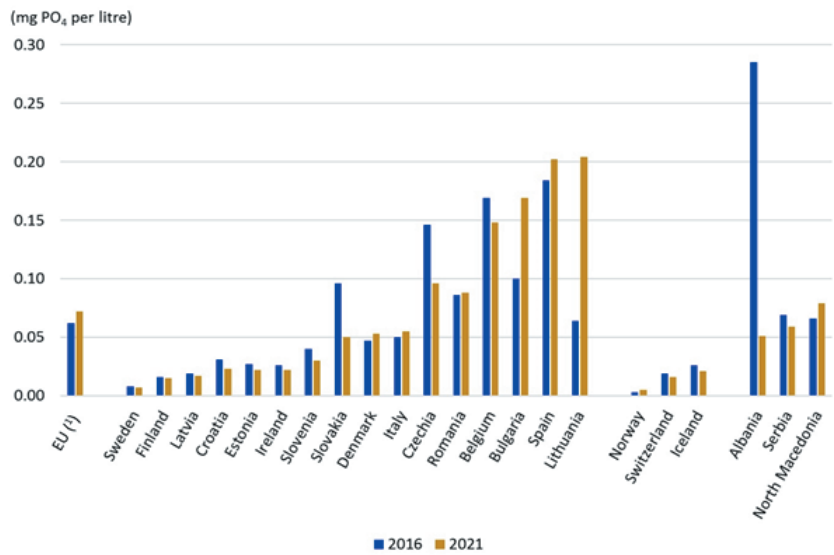

Figure 3. Phosphate in rivers, by country, 2016 and 2021 (mg PO_4 per litre) [18]. (Fig. 10 in [18])

The biochemical oxygen demand levels (O_2 [mg/l]), indicative of organic pollutants, have generally decreased (Figure 1 [18]), reflecting successful upgrades in wastewater treatment facilities and better industrial practices.

However, the persistent presence of nutrients—specifically nitrates and phosphates—remains a substantial environmental and public health concern [19]. Average nitrate concentrations in groundwater (NO_3 [mg/l]) have stabilized around 20.5 mg/l, continuously challenging the EU's goal to significantly reduce nutrient loads and prevent eutrophication (Figure 2 [18]).

Meanwhile, phosphate concentrations (PO_4 [mg/l]) in river systems have risen sharply, by 21.3 % since 2016, predominantly due to intensified agricultural activities, suboptimal wastewater treatment in rural and peri-urban areas, and inconsistent enforcement of environmental regulations (Figure 3 [18]).

The climatic impact on freshwater resources, notably through drought events, has exacerbated water scarcity conditions across the EU. Approximately 29 % of EU territory now experiences severe water stress periodically, with pronounced regional disparities influenced by climate variability, population density, agricultural demand, and tourism. Countries in southern Europe, such as Cyprus and Malta, experience particularly high water exploitation indices, indicating unsustainable freshwater use. This finding underscores the critical need for adaptive management strategies and climate resilience planning, in EU and other countries, e.g. Ireland [15].

A comparative analysis involving Serbia highlights broader challenges that extend beyond EU borders, emphasizing pronounced gaps in wastewater treatment infrastructure and persistent nutrient pollution. Serbia's lower connectivity rates to advanced wastewater treatment and elevated nutrient loads in water bodies further stress the urgency of cross-border policy integration and regional cooperation.

Policy effectiveness across the EU varies, with notable successes tempered by ongoing implementation gaps. Enhanced enforcement of existing directives increased financial investments in infrastructure, particularly in rural and lower-density regions, and proactive climate adaptation measures are crucial for improving freshwater sustainability. Future policies should prioritize integrated water resource management, leveraging technological innovation and fostering cross-regional collaborations to address the intertwined challenges of water quality, climate change, and infrastructure deficits comprehensively [3], [4], [8], [20].

4. CONCLUSION

This study emphasizes the substantial progress achieved in the EU wastewater treatment infrastructure over recent decades, while simultaneously highlighting persistent challenges in maintaining water quality amid increasing climate-induced water stress. Significant enhancements in treatment connectivity and advanced processing methods have contributed to reductions in organic pollutants, yet issues such as eutrophication remain prevalent due to elevated concentrations of nutrients, specifically nitrates and phosphates. These findings indicate that while infrastructural developments have been successful in mitigating some aspects of water pollution, the management of nutrient loads continues to be a critical environmental concern.

Furthermore, the impacts of climate variability have intensified the stress on freshwater resources, as prolonged droughts and erratic precipitation patterns exacerbate water scarcity and quality degradation. The evidence suggests that adaptive management strategies must be integrated into current water resource policies to effectively address the dual challenges of nutrient pollution and climatic stress. Enhancing monitoring capabilities and predictive modelling is essential to better understand the temporal dynamics of pollutant dispersion and the influence of extreme weather events on water systems.

Recommendations emerging from this study advocate for increased investment in wastewater treatment infrastructure to expand capacity and improve operational efficiency. Moreover, the enforcement of environmental regulations requires strengthening to ensure consistent application of policies across different regions. Enhanced regional cooperation is also imperative, as coordinated efforts among EU member states and neighbouring regions can facilitate the sharing of best practices and the development of integrated water management strategies. Such collaborative approaches are vital for establishing resilient water systems capable of sustaining both ecological integrity and public health in the face of evolving environmental pressures. Collectively, these measures provide a comprehensive framework for promoting sustainable freshwater management both within the EU and in broader international contexts.

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