

Article

The Development of Inland Waterway Transport as a Key to Ensuring Sustainability: A Geographic Overview of the Bucharest–Danube Canal

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Abstract: Inland waterway transport faces increasing recognition as a sustainable alternative to conventional transport modes, particularly due to its lower environmental impact and higher efficiency. However, its implementation remains limited in many regions, including Romania, despite substantial potential benefits. This study addresses this gap by assessing the Bucharest–Danube Canal as a strategic infrastructure project capable of supporting Romania’s transition to sustainable transport, aligned with the European Green Deal and the United Nations 2030 Agenda. Employing a structured methodological approach, this research includes a comprehensive literature review and detailed analysis of successful European inland waterway transport projects, systematically correlating findings with specific Sustainable Development Goals. The results illustrate clear relationships between the selected case studies and the targeted goals, highlighting approaches for integrating sustainability into waterway infrastructure. Specifically, the study identifies effective guidelines applicable to Romania and emphasizes the necessity of a comprehensive, multi-dimensional planning approach that exploits the canal’s multifunctional capabilities beyond transportation, encompassing agriculture, tourism, renewable energy, and biodiversity conservation. In conclusion, despite historical and current challenges, the Bucharest–Danube Canal represents a strategic opportunity for Romania, promising significant contributions toward achieving national and regional sustainability objectives.

Keywords: sustainable transport; inland waterway transport; sustainable development goals; Bucharest–Danube Canal; Romania



Academic Editors: Chunhui Zhou, Hongxiang Feng, Fan Zhang and Zhongyi Sui

Received: 8 April 2025

Revised: 25 April 2025

Accepted: 10 May 2025

Published: 13 May 2025

Citation: Luca, G.-G.; Guju, D.-I.; Comănescu, L. The Development of Inland Waterway Transport as a Key to Ensuring Sustainability: A Geographic Overview of the Bucharest–Danube Canal. *Sustainability* **2025**, *17*, 4438. <https://doi.org/10.3390/su17104438>

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1. Introduction

Inland waterway transport (IWT) is increasingly recognized as a strategic pillar in the transition toward more sustainable and integrated transportation systems [1–7]. As a mode that combines high freight capacity with low environmental impacts, IWT holds significant potential to address pressing challenges related to emissions reduction, energy efficiency, and spatial equity [2,6,8,9]. Its relevance is particularly evident in the context of global and regional efforts to decarbonize transport infrastructure and reconfigure mobility systems around principles of sustainability and resilience.

The broader context in which IWT operates is marked by mounting pressures on conventional transport systems [5,10,11]. Transportation remains essential to socio-economic development, facilitating the movement of goods, people, and services, underpinning both local economies and global trade networks [12–14]. However, the rapid expansion of

transport activities has come at a cost: increased greenhouse gas emissions, urban congestion, and an over-reliance on fossil fuels continue to undermine environmental quality and social well-being [11,15]. These issues have triggered an urgent need for more sustainable transport solutions capable of balancing economic growth with environmental stewardship and social inclusion.

Policy frameworks, such as the European Green Deal and the United Nations 2030 Agenda for Sustainable Development, call for a fundamental shift in the way transport infrastructure is planned and managed, emphasizing multimodality, climate neutrality, and territorial cohesion [16]. Within this paradigm shift, IWT emerges as a particularly effective tool for reducing transport-related emissions and easing pressure on road and rail networks. By offering lower energy consumption per ton-kilometer and fewer emissions compared to road or air transport, inland navigation aligns well with these policy goals [17–21].

Beyond its environmental benefits, IWT also supports broader socio-economic objectives. It enables efficient freight logistics, fosters regional development through its integration with local industries and agriculture, and promotes alternative forms of tourism and recreation [22–24]. As such, IWT represents not only a viable transport solution but also a spatial and developmental asset capable of addressing multiple sustainability goals.

However, while the alignment of IWT with sustainability objectives is well established, its practical integration into multimodal systems requires more than environmental vision and technical feasibility [25–28]. It demands a policy-oriented analytical framework that critically addresses the governance, planning, and infrastructural constraints impeding operationalization at national and transnational levels. These constraints include institutional fragmentation, inconsistent regulatory frameworks, and limited intermodal infrastructure, particularly in peripheral or transition economies.

To fully appreciate these challenges, it is necessary to revisit the early 2000s—a formative period in EU transport policy, marked by the launch of the 2001 White Paper on European Transport Policy [29] and the establishment of the Trans-European Transport Network (TEN-T) [30] as a strategic infrastructure backbone. Although these instruments promoted modal shift and emphasized multimodality, evaluations by both the European Commission and the European Court of Auditors have repeatedly noted the limited progress made in intermodal integration, especially regarding inland waterway infrastructure and its connection with ports and hinterlands [25–27].

In this context, Schinas and Dionelis [31] offer a critical perspective on the specialized planning needs of sea–river and sea–rail interconnections. Their research emphasizes the asymmetries in planning and coordination challenges that hinder the development of integrated transport systems. They argue that effective integration of IWT into broader multimodal networks requires not only technical feasibility and environmental alignment, but also a policy-driven framework that addresses governance gaps, particularly in regions where transport sectors have developed in isolation. Their work is particularly relevant in the context of southeastern Europe, where institutional fragmentation and lack of coordinated investments have been major barriers to developing efficient, interconnected transport infrastructure, including IWT.

The authors also highlight the risks of misaligned investments and the need for cross-sectoral coordination between different transport authorities to optimize infrastructure development. These challenges are consistent with the issues identified in the EU’s strategic documents and point to the need for a comprehensive approach that incorporates IWT as a key component in sustainable, multimodal transport systems.

Understanding these regulatory and infrastructural shortcomings also requires attention to the physical characteristics and spatial configurations of inland waterway networks. Unlike road or rail systems, inland navigation infrastructures are highly dependent on nat-

ural hydrological features, existing land uses, and regional planning constraints. As such, the integration of IWT into multimodal strategies is shaped not only by policy alignment, but also by the structural typologies of the waterways themselves.

Understanding the typological diversity of IWT systems provides a useful context for analyzing their role within national and regional transport frameworks. According to the United Nations Economic Commission for Europe (UNECE) [32], IWT is categorized into three main types based on the infrastructure used for navigation: free-flowing rivers; canalized rivers; and canals (Figure 1). Each category plays a distinct role within the broader IWT system, enabling the movement of goods and people across inland regions.

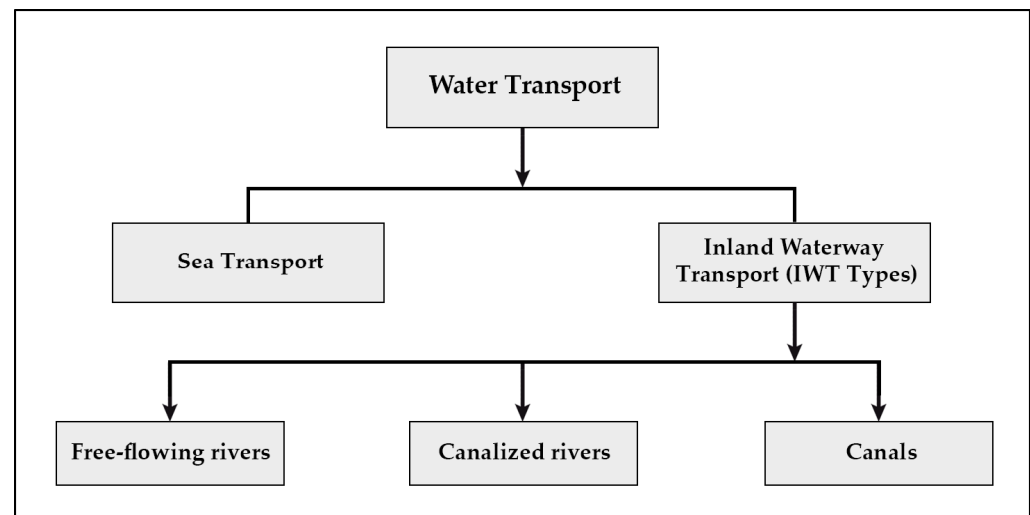


Figure 1. Classification of water transport, highlighting the three main types of IWT: free-flowing rivers; canalized rivers; and canals. Source: authors’ compilation based on data from UNECE [32].

Free-flowing rivers are natural watercourses that do not require significant modifications for navigation. These rivers typically have an unobstructed flow, allowing vessels to navigate without the need for extensive engineering works such as dams or locks. Their navigability is largely determined by natural factors such as water levels and seasonal fluctuations [32,33].

Canalized rivers are natural rivers that have been modified to improve navigability and facilitate transportation. These modifications usually involve the construction of locks, dams, and channelization to regulate water flow and ensure consistent navigation. Canalized rivers are crucial for long-distance inland waterway transport, providing a more predictable and reliable route compared to free-flowing rivers [32,33].

Canals are artificially constructed waterways designed to connect rivers, ports, or regions, often overcoming natural obstacles like difficult terrain or unreliable watercourses. Unlike natural rivers, canals provide controlled navigation and are integral to multimodal transport systems, ensuring efficient connectivity and regional integration. They are typically engineered to meet specific logistical needs and provide consistent and predictable routes [32,33].

While river transport remains essential for regional mobility and trade, canalized rivers distinguish themselves by being modified for improved navigability. Canals are specifically engineered to overcome topographic barriers, extend navigable networks, and integrate isolated or landlocked regions into broader transport and economic systems. In this context, canals have long served as key enablers of regional development and are now increasingly recognized as critical infrastructure for achieving decarbonization and multimodal integration goals.

Canals

This study specifically focuses on the role of canals as an essential component of the inland waterway network. Canals represent engineered segments of the inland waterway network, facilitating the continuity and efficiency of water transport. While IWT refers to the broader system of freight and passenger movement via navigable inland waters, canals are essential structural components that bridge non-navigable terrains, ensuring operational connectivity and spatial integration [34].

From the earliest canals built in antiquity to the major modern projects of the twentieth and twenty-first centuries, navigable canals have marked significant progress in the fields of hydraulic engineering and river transport [35,36]. Historically, these man-made waterways have been critical in shaping the economic and cultural landscapes of civilizations. Early canals facilitated the irrigation of arid lands, supported military logistics, and enabled the transport of agricultural surpluses, which in turn laid the foundation for urbanization and the growth of trade networks [37,38]. Over the centuries, the development of navigable waterways has continued to evolve, reflecting advancements in engineering and changes in economic priorities. An emblematic example of modern engineering is the Rhine–Main–Danube Canal, a flagship project within the European inland waterway network [23,39]. Completed in 1992, this canal connects the Rhine with the Danube, thereby enabling continuous navigation from the North Sea to the Black Sea. This remarkable achievement not only strengthened commercial links between western and eastern Europe but also enhanced the efficiency of intermodal transport systems by providing a reliable alternative to road and rail [8,13]. Numerous studies have analyzed the economic, social, and ecological impacts of the Rhine–Main–Danube Canal, underscoring its strategic importance for European trade, regional development, and environmental sustainability [19].

As efforts to combat climate change intensify, the relative advantages of IWT in lowering greenhouse gas emissions become increasingly significant [6,40,41]. In addition, an important line of inquiry in the literature concerns the integration of navigable canals into broader strategies for preserving industrial and cultural heritage. Historical canals are now frequently classified as part of a region's technical heritage due to their multifaceted value, which encompasses technological, economic, social, and landscape-related contributions [42]. Technologically, these canals were designed to serve various functions such as navigation, irrigation, water supply, and flood prevention. Economically, they have been instrumental in facilitating the growth of key sectors, including freight transport, industry, agriculture, and tourism, thus acting as catalysts for regional development. Socially, these infrastructures have fostered mobility and cultural interactions, while the scenic landscapes they create offer unique opportunities for tourism and the sustainable utilization of natural and cultural resources. This integrated perspective on canals underscores their role as vital, multi-functional assets that contribute to the sustainable development of both urban and rural areas [43–45].

At the global level, navigable canals are increasingly recognized as essential components of multimodal transport networks that enable efficient inter-regional connections and facilitate international trade flows. For instance, an extensive analysis by Wang et al. (2020) of major global canals identified the Rhine, Volga, Yangtze, Pearl, and Amazon basins as critical axes that significantly impact economic activity and infrastructure development [46]. These canal systems are not merely isolated transport routes; they are integrated into complex networks that support the movement of goods across continents, thereby reinforcing global supply chains. While early research on sustainable waterway development focused predominantly on established networks in Europe and Asia, recent studies have expanded to include emerging contexts in developing countries such as India, Indonesia, Nigeria, and Nepal [47–50]. In regions like South America, where vast hydrographic basins, such

as the Amazon, Orinoco, Paraná, and Magdalena are present, the scientific literature on navigable infrastructure remains relatively limited. This gap is often attributed to factors, such as insufficient investments, institutional challenges, and underdeveloped legislative frameworks, that collectively hinder the full exploitation of inland waterway potential for sustainable transport.

At the national level, Romania presents a particularly compelling case for the development of IWT as a driver for sustainable development. Despite possessing an extensive network of waterways that historically have contributed to the nation's economic and cultural evolution, the full potential of navigable canals remains underexplored. Projects, such as the Danube–Black Sea Canal, have received considerable attention due to their role in alleviating congestion on the Danube and providing alternative maritime routes, which have significantly contributed to regional economic development and the modernization of transport infrastructure [51,52]. However, other initiatives—most notably the Bucharest–Danube Canal—have not been examined with comparable breadth and depth. This research gap has hindered the integration of IWT into Romania's broader sustainable development strategies, even as the country faces increasing pressure to decarbonize its transport sector and diversify its regional economies.

The aim of this study is to explore the potential of the Bucharest–Danube Canal to contribute to Romania's sustainable transport objectives by contextualizing it within broader European experiences of canal development. The evolution of multifunctional canal infrastructure within contemporary IWT networks provides a valuable analytical lens, highlighting three essential conditions for success: intermodal integration; adaptive water management; and multi-actor governance.

2. Materials and Methods

2.1. Study Area

The Bucharest–Danube Canal is a strategic inland waterway in southern Romania, envisioned to establish a direct navigable link between Bucharest and the Danube River. By integrating the capital into Europe's inland waterway network, the canal could enhance regional and international connectivity, facilitating trade and strengthening Romania's role in transcontinental transport corridors [53]. As part of a broader multimodal infrastructure strategy, it would support the shift from road-based freight transport to more sustainable inland navigation, aligning with European Union policies on economic and environmental sustainability.

At the national level, the canal would provide Bucharest with direct access to the Danube, improving its logistical integration with major commercial hubs. Following the courses of the Argeş and Dâmboviţa Rivers, it would create a navigable corridor that connects the capital to key domestic and international transport routes. This infrastructure could generate economic benefits by fostering industrial development, optimizing freight transport, and supporting tourism [54,55]. Additionally, it may contribute to environmental resilience by reducing carbon emissions, improving water management, and enhancing regional ecological stability.

Through its geographical location (Figure 2), the Bucharest–Danube Canal has the potential to transform regional mobility, positioning Bucharest as a key node in the European inland navigation system [1,56]. In addition to its main role in transportation, the canal was planned to provide various economic and environmental advantages such as moving goods and people by water, generating electricity with small hydroelectric plants, supporting farming with irrigation, controlling floods for nearby areas, and ensuring a steady water supply for local communities [35]. Additional projected benefits included the enhancement of pisciculture, the development of tourism infrastructure, and broader

ecological restoration initiatives aimed at improving regional water management and biodiversity conservation.

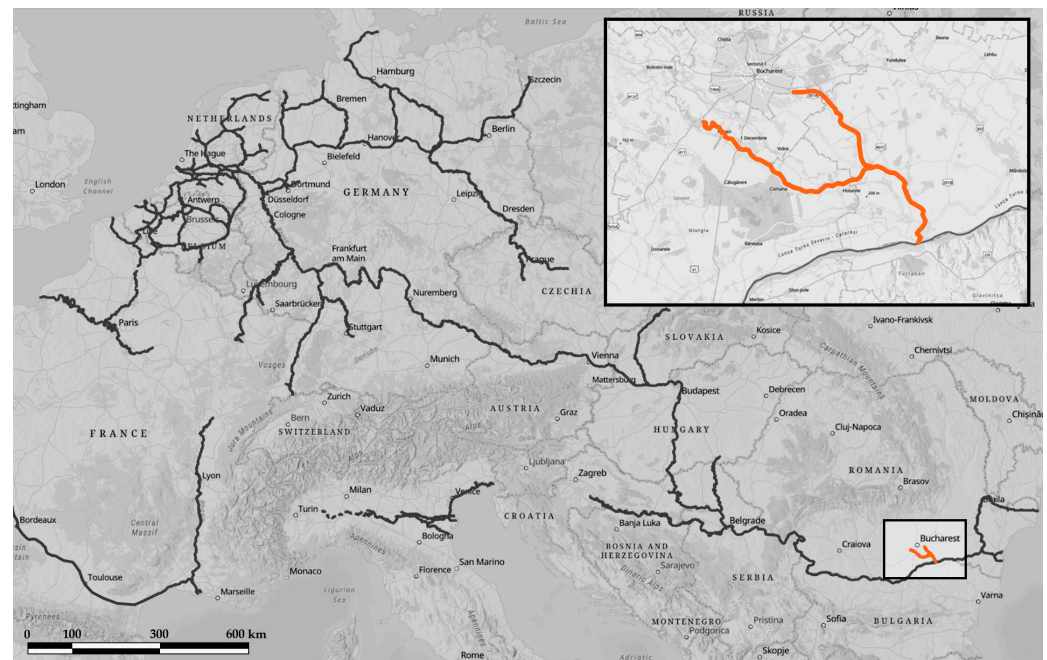


Figure 2. An overview map of Europe’s IWT, highlighting the proposed Bucharest–Danube Canal in orange. This canal is envisioned to connect Romania’s capital directly to the Danube River. Source: authors’ compilation based on data from the European Commission TEN-T Regulation [53].

2.2. History and Evolution of the Bucharest–Danube Canal

The strategic vision of creating a navigable link between Bucharest and the Danube River dates back to the 19th century, reflecting long-standing efforts to integrate Romania’s capital into the European inland waterway network. The first recorded proposal for such a canal was made in 1864, when a group of French investors suggested the construction of a navigable route connecting Bucharest to the Danube. However, it was not until 1880 that engineer Nicolae Cucu developed the first known technical draft for a waterway linking the capital to Oltenița, a major port at the confluence of the Argeș River with the Danube [57,58].

Throughout the early 20th century, the concept of the Bucharest–Danube Canal remained a subject of considerable technical and political debate. In 1927, Professor Alexandru Davidescu published a study on the project’s feasibility, followed shortly by a report from engineer Dimitrie Leonida, both advocating for its construction. By 1929, the Romanian Parliament formally recognized the canal’s strategic importance and adopted a Law on the Construction of the Argeș–Bucharest–Danube Canal, promulgated on 31 July 1929 and published in the Official Gazette No. 170 on 8 August 1929. The plan was ambitious, aiming to enhance the capital’s economic reach and facilitate commercial navigation along the Danube. However, financial constraints and the economic downturn of the early 1930s prevented the project from advancing beyond preliminary studies [57,59].

Interest in the canal resurged during the mid-20th century, particularly in the post-World War II period, when large-scale infrastructure projects were prioritized to support economic recovery and industrialization. Between 1960 and 1980, numerous hydrological and engineering studies were conducted, focusing on the efficient management of water resources in southern Romania [57,58].

In 1982, under the directives of the Romanian government, a dedicated planning commission was established within the Institute of Transport Studies to oversee the canal’s

design and implementation. Extensive field studies, including topographical surveys, geological assessments, and hydrological analyses, were conducted to determine the optimal route and engineering solutions. The planning phase examined multiple potential locations for Bucharest's main port, with proposed sites including Cornetu, Jilava, and Glina. Eventually, the area near 1 Decembrie was selected due to its strategic position along the Argeş River [58].

Construction officially began in 1986, supported by a large-scale workforce and significant state investments. The project aimed to regulate the lower Argeş and Dâmboviţa Rivers to create a stable, navigable route, integrating hydroelectric plants, flood control systems, and irrigation networks. By 1989, extensive excavation and structural work had been completed, including the construction of embankments, sluices, and preliminary port facilities [60]. However, following the political changes in Romania in 1990, funding for the canal was abruptly halted, leading to the suspension of all construction activities.

Since then, the partially completed infrastructure has remained in a state of neglect. Various studies and feasibility assessments have been conducted in subsequent years, evaluating the potential for project resumption. In 2012, a revised feasibility study was carried out, reaffirming the canal's potential role in economic development, sustainable transport, and regional connectivity. Nevertheless, the lack of political consensus and investment has continued to delay any substantial progress toward its finalization.

Despite its incomplete status, the Bucharest–Danube Canal remains a significant element in Romania's infrastructure agenda. It represents a key opportunity for integrating the country into the European inland waterway network, providing economic, environmental, and logistical benefits [61–63]. Understanding the historical trajectory of the canal is crucial for shaping future development strategies, ensuring that past lessons inform modern infrastructure planning and decision making.

2.3. Methodology

The study adopts a structured methodological approach designed to support a comprehensive understanding of IWT systems and their role in regional sustainable development. This research is grounded in an extensive review of interdisciplinary sources, including academic literature, cartographic materials, planning documents, development strategies, technical reports, and archival records. The framework aims to assess the multifunctional potential of IWT infrastructure by addressing its economic, environmental, and social dimensions, with a particular emphasis on its relevance for future development initiatives such as the Bucharest–Danube Canal.

To enhance the analytical depth and relevance of the study, the approach incorporates perspectives drawn from selected European case studies, which will be examined in the following chapters. These serve to contextualize the Romanian case within broader European practices and to identify key conditions that have enabled similar projects to contribute to sustainable regional transformation.

This methodology offers several advantages. It supports the transfer of strategic knowledge, facilitates the identification of critical success factors, such as multimodal integration, governance structures, and environmental safeguards, and provides a foundation for informed decision making. By aligning empirical analysis with contextual understanding, the study seeks to generate policy-relevant insights that are both locally grounded and broadly applicable.

The conceptual structure of this research is informed by the work of Barros et al. [64], whose taxonomy of sustainability issues related to IWT provides a solid theoretical and methodological foundation. Drawing upon their framework, six Sustainable Development Goals (SDGs) from the United Nations 2030 Agenda were identified as particularly relevant

to this analysis: positive health and well-being (Goal 3); clean water and sanitation (Goal 6); decent work and economic growth (Goal 8); industry, innovation and infrastructure (Goal 9); sustainable cities and communities (Goal 11); and climate action (Goal 13). The selection of these goals, as proposed by Barros et al. [64], reflects the multidimensional impact of IWT infrastructure and serves in the present study as a foundation for assessing how canal-related projects may align with and support broader sustainability objectives. The methodological structure adopted in this research is synthesized in the schematic diagram below (Figure 3).

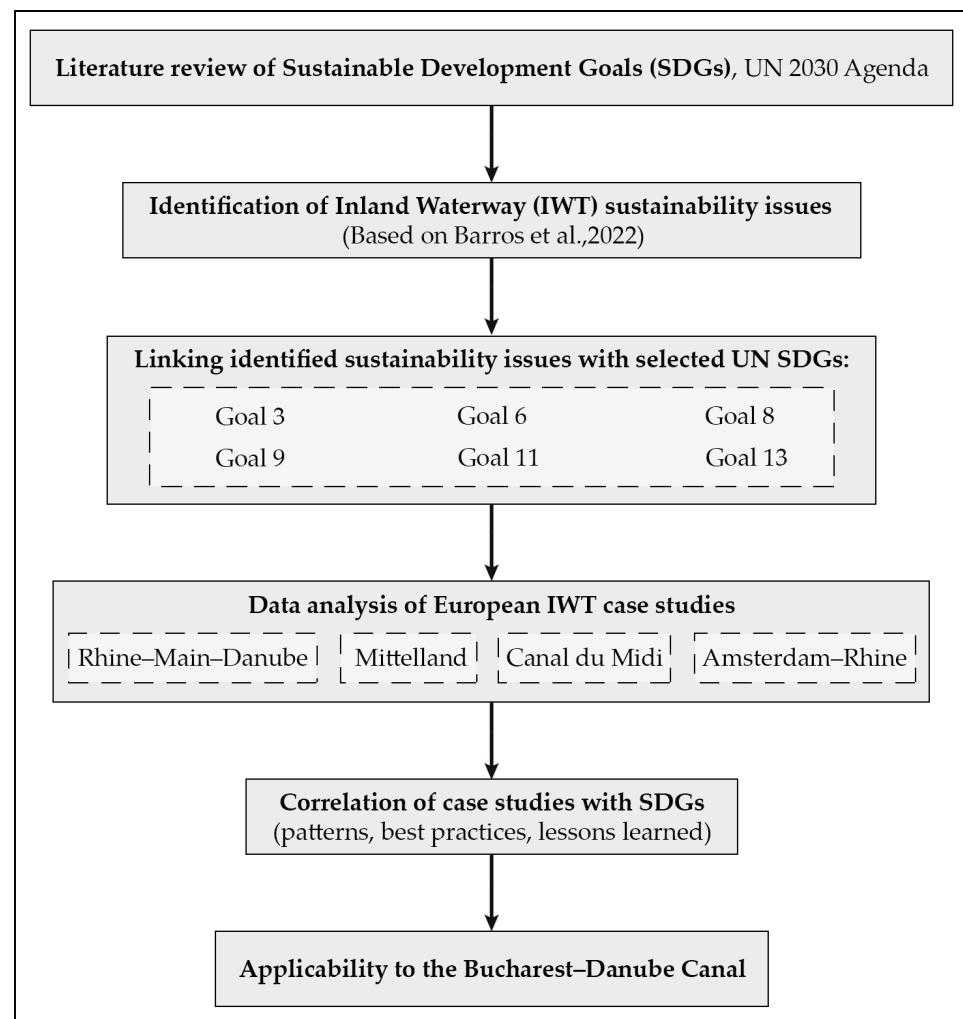


Figure 3. Schematic representation of the research methodology. Source: authors' work [64].

It outlines the sequential stages followed throughout the study. Starting from a literature review of the SDGs [16], the framework identifies key sustainability issues related to IWT, as defined by Barros et al. [64]. These issues were then mapped against a selection of six SDGs considered most relevant to IWT. Subsequently, data were collected and analyzed from four European case studies, allowing for the identification of recurring patterns, good practices, and strategic insights. The framework concludes with an assessment of the potential transferability of these insights to the context of the Bucharest–Danube Canal.

3. Results

To explore the role of IWT in advancing sustainable development, this section conducts a comprehensive analysis of four European canal systems: the Rhine–Main–Danube Canal, the Mittelland Canal, the Canal du Midi, and the Amsterdam–Rhine Canal. Their

diversity in terms of geography, function, and infrastructure allows for a comprehensive and multidimensional assessment of how inland navigation systems can contribute to broader sustainability goals.

3.1. Rhine–Main–Danube Canal

The Rhine–Main–Danube Canal is a 171 kilometer-long inland waterway situated in southern Germany (Figure 4), linking the Main River (a tributary of the Rhine) with the Danube River [65]. Completed in 1992, the canal forms a vital component of the Trans-European Transport Network (TEN-T), creating a navigable corridor between the North Sea and the Black Sea that spans over 3500 kilometers. Its central geographical location positions it at the core of continental Europe, facilitating the seamless integration of IWT across multiple countries.

The canal enhances both regional and international freight transport while also serving as a backbone for multimodal connectivity and sustainable infrastructure development [39,65,66].

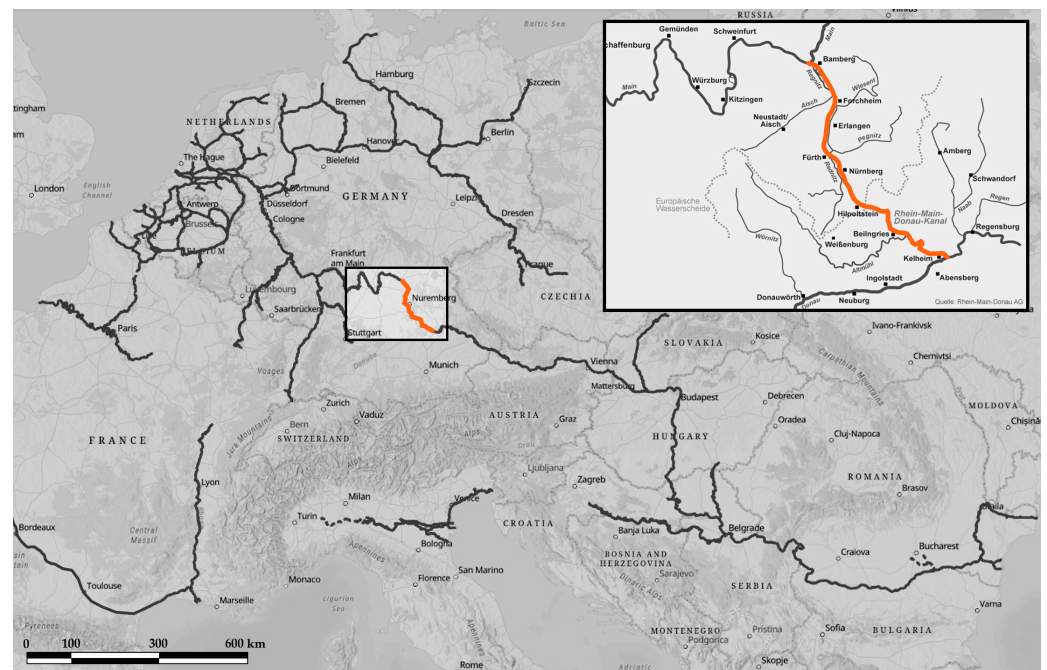


Figure 4. Overview of the Rhine–Main–Danube Canal, connecting the Main River at Bamberg to the Danube River at Kelheim. Source: authors' compilation based on data from the European Commission TEN-T Regulation [53] and Danube Culture [67].

Since its completion, the Rhine–Main–Danube Canal has significantly contributed to regional logistics performance and environmental sustainability. On average, 5 to 7 million tons of cargo are transported through the canal annually, accounting for nearly 9% of Europe's total inland freight volume [68,69].

The modal shift from road to water transport has led to marked reductions in greenhouse gas emissions, given that IWT emits 4 to 6 times less CO₂ per ton-kilometer than road freight. It is estimated that the canal helps to avoid approximately 1600 tons of CO₂ per kilometer of cargo moved when compared to trucking operations [70,71].

Additionally, the infrastructure supports numerous ports and intermodal terminals, fostering the development of logistics hubs and promoting job creation along its length [70]. These effects are amplified by complementary investments in related sectors such as tourism, leisure navigation, and flood protection. The canal has also contributed to social

improvements, such as enhanced road safety, due to reduced heavy vehicle traffic and improved air quality in urban zones adjacent to its corridor [71].

To illustrate the logistical performance of the Rhine–Main–Danube Canal (Table 1), estimated travel times between Rotterdam (Netherlands) and Constanța (Romania) for various types of inland vessels are presented. Although travel durations may appear relatively long compared to other transport modes, the high freight capacity of inland convoys and significantly lower environmental impact make this waterway a sustainable alternative. The canal enables the movement of large cargo volumes with reduced emissions, aligning with broader climate and energy efficiency goals.

Table 1. Travel time between Rotterdam and Constanța via the Rhine–Main–Danube Canal. Source: Chiroșcă and Rusu [65].

Vessel Type	Operation Mode	Distance [km]	Locks	Time Rotterdam–Constanța	Time Constanța–Rotterdam
Motor cargo vessel 1350 to. Tonnage	24 h	3253	70	11 days and 18 h	14 days and 3 h
Motor cargo vessel 2000 to. Tonnage	24 h	3253	70	11 days and 7 h	12 days and 11 h
2-unit pushed convoy	24 h	3253	70	12 days and 20 h	14 days and 2 h
4-unit pushed convoy	24 h	3253	70	– *	– *

* Not operating due to restricted maximum dimensions of vessels and pushed convoys.

A set of directly and indirectly relevant SDGs was first identified. This classification emerged from a thorough review of the scientific literature on IWT, with a particular emphasis on recurring themes in sustainability-focused studies [1,5,11,27,39,56,65,72]. The taxonomy proposed by Barros et al. [64] served as a conceptual foundation, while the final selection was refined through cross-analysis with the findings of the European case studies included in this research.

The Rhine–Main–Danube Canal aligns directly with several SDGs; specifically, it supports SDG 8 (Decent Work and Economic Growth) through employment generation and regional economic stimulation along its route. It contributes to SDG 9 (Industry, Innovation and Infrastructure) by fostering resilient infrastructure and promoting innovation in multimodal logistics. In terms of climate-related benefits, the canal strongly addresses SDG 13 (Climate Action) through its substantial reduction in CO₂ emissions and role in climate-adaptive transport planning.

Indirectly, the canal supports SDG 11 (Sustainable Cities and Communities) by enhancing urban livability, SDG 3 (Good Health and Well-being) through reduced pollution levels, and SDG 6 (Clean Water and Sanitation) by integrating water management practices into its operational systems.

The Rhine–Main–Danube Canal exemplifies the transformative potential of inland waterway infrastructure when aligned with sustainability principles. Through its strategic integration into the TEN-T network and consistent contributions to economic, environmental, and social domains, it demonstrates how such projects can serve as benchmarks for similar initiatives.

For the future development of inland navigation corridors, such as the Bucharest–Danube Canal, this case study underscores the importance of comprehensive planning, cross-sector collaboration, and alignment with the United Nations 2030 Agenda for Sustainable Development.

3.2. Mittelland Canal

The Mittelland Canal is the longest artificial waterway in Germany, stretching approximately 325 kilometers from the Dortmund–Ems Canal near Hörstel in the west to the Elbe River near Magdeburg in the east (Figure 5). Functioning as a crucial component of Germany’s inland waterway network, the canal facilitates east–west freight movement and connects major industrial centers in western Germany with the Elbe and, indirectly, the Oder and Vistula basins [73]. It is also an integral part of the broader TEN-T, serving as a catalyst for multimodal integration and enhancing continental trade routes [1].

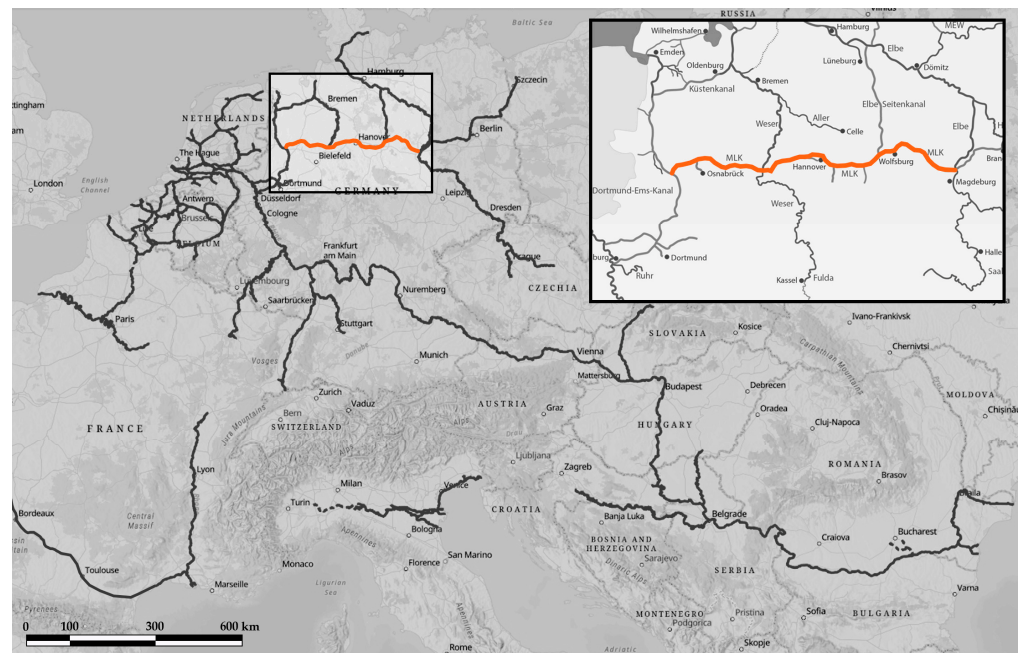


Figure 5. The Mittelland Canal connects the Dortmund–Ems Canal near Hörstel to the Elbe River near Magdeburg. Source: authors’ compilation based on data from the European Commission TEN-T Regulation [53] and Water-Ways [74].

The Mittelland Canal is the backbone of Europe’s east–west inland waterway axis, linking the Rhine, Ems, Weser, Elbe, and Oder basins. It is the most trafficked canal in Germany, handling nearly 50% of national canal freight volume [74,75].

Between 2005 and 2017, annual freight ranged from 20 to 23 million tons, with stable volumes continuing today (Figure 6). Its integration with intermodal terminals in cities like Hanover and Braunschweig enhances freight efficiency and relieves pressure on road and rail networks [76].

The canal has played a pivotal role in water management strategies across northern Germany. Its regulatory functions contribute to flood prevention and support agricultural irrigation in adjacent areas. The infrastructure has been continuously modernized, with investments in lock renewal, embankment reinforcement, and waterway deepening aimed at supporting larger and more energy-efficient vessels [66]. These enhancements have helped to cut fuel consumption and greenhouse gas emissions while improving overall transport reliability.

The canal’s integration with urban areas has also led to improvements in land use planning, recreational development, and environmental restoration, with green corridors and wildlife habitats established along its banks. Initiatives, such as riverbank renaturation and noise reduction programs, have further enhanced the canal’s role in sustainable spatial development [77].

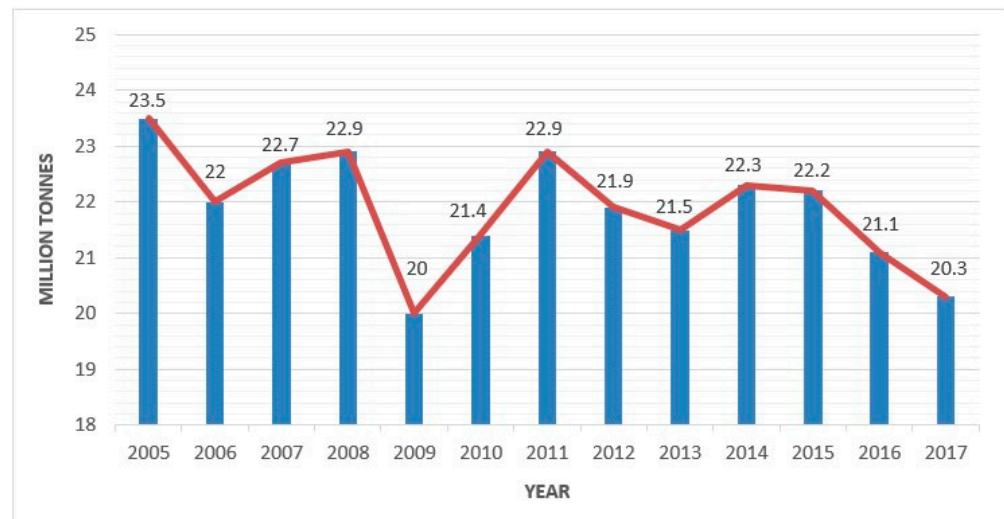


Figure 6. Annual freight volume transported on the Mittelland Canal (in million tons). Source: authors' compilation based on data from Rolbiecki and Wojewódzka-Król [76].

Based on the taxonomy proposed by Barros et al. [64], and additional findings in the literature [5,11,27,72,75,76,78], the Mittelland Canal demonstrates a strong alignment with the following SDGs: SDG 6 (Clean Water and Sanitation); SDG 9 (Industry, Innovation and Infrastructure); and SDG 11 (Sustainable Cities and Communities). The canal's water management functions contribute to SDG 6 by supporting regulated water flow and improving water quality in surrounding regions. Through investments in infrastructure modernization and intermodal facilities, it also advances SDG 9 by promoting innovation and resilience in transport systems. Furthermore, its integration into urban planning and recreational spaces strengthens SDG 11 by enhancing quality of life. Indirect contributions can be observed in SDG 13 (Climate Action), particularly through modal shifts that decrease road freight and associated emissions, and in SDG 8 (Decent Work and Economic Growth), via the canal's role in supporting regional economic activities and employment.

The Mittelland Canal illustrates how long-established infrastructure can be adapted to meet contemporary sustainability goals. The case demonstrates the value of sustained investment, policy alignment, and intermodal synergy in creating inland waterway systems that are not only economically productive but also environmentally and socially responsible. Its lessons are particularly instructive for the future development of inland waterways, like the Bucharest–Danube Canal, where multifunctional design and cross-sector integration remain key to sustainable implementation.

3.3. Canal du Midi

The Canal du Midi is a historic inland waterway located in southern France, connecting the Garonne River at Toulouse to the Mediterranean Sea near Sète (Figure 7). Constructed between 1666 and 1681, the 240 km canal crosses the Occitanie region and was initially designed to create a navigable route between the Atlantic Ocean and the Mediterranean, avoiding the Strait of Gibraltar [79]. Today, it forms part of the wider French inland waterway system, facilitating slow tourism and heritage conservation rather than commercial freight transport.

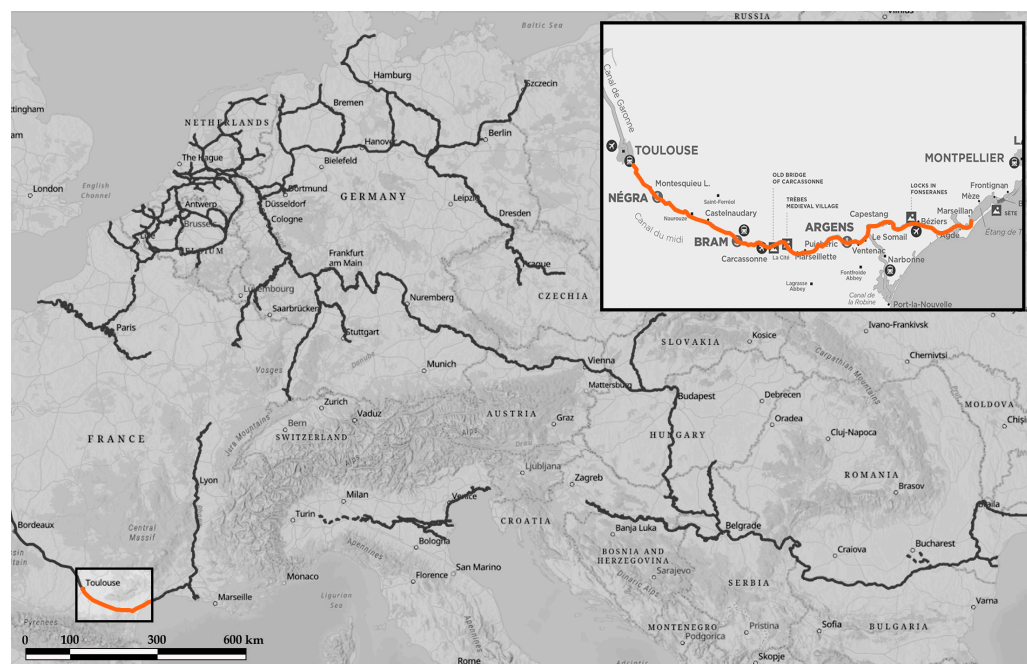


Figure 7. Overview of the Canal du Midi, connecting the Garonne River at Toulouse to the Mediterranean Sea near Sète. Source: authors' compilation based on data from the European Commission TEN-T Regulation [53] and French Waterways [80].

Recognized as a UNESCO World Heritage Site since 1996, the canal is not only a technical and historical achievement but also a driver of cultural and economic activity in rural and semi-urban areas. The Canal du Midi continues to serve multiple roles, including tourism, landscape preservation, irrigation, and heritage infrastructure reuse [81]. Despite no longer being a major cargo route, its socio-economic relevance remains strong, exemplifying how historical water infrastructure can be repurposed in line with sustainable development objectives. Since its transformation into a heritage and tourism corridor, the Canal du Midi has become a key contributor to the local economy and ecological preservation efforts. It receives approximately 1.5 million visitors annually, with around 45,000 tourists navigating its waters aboard rental boats or hotel barges [37]. The canal contributes an estimated 122 million euros to the local economy each year and supports approximately 2000 direct jobs in sectors such as boat maintenance, hospitality, and recreational services [37,82].

Beyond its transport role, the Canal du Midi functions as a green corridor with documented contributions to regional air quality. Since 2024, over 19,000 trees have been replanted along its banks, with 1300–1500 new trees added annually through a 200-million euro restoration program aimed at ecological renewal and landscape preservation. The green buffers act as biological filters, capturing PM_{2.5} particles and absorbing NO₂ and CO₂, which are major urban air pollutants. Studies on comparable urban green infrastructures indicate potential reductions of up to 25% in particulate matter and 40% in nitrogen dioxide concentrations [83]. In parallel, the canal integrates into a broader ecological system, connecting to nature reserves and adjacent rivers, thereby enhancing biodiversity and natural air purification processes within the region [79]. Moreover, waterborne transport activities along the canal generate up to four times less CO₂ emissions than road transport, further reinforcing its environmental value [84].

Additionally, the canal plays a role in irrigation and local water management, helping to regulate flows in an increasingly climate-vulnerable region [79]. Its environmental impact

is also seen in its promotion of eco-tourism, with extensive cycling paths and pedestrian zones established along the canal corridor (Figure 8).



Figure 8. A section of the Canal du Midi, featuring cycling and pedestrian paths that support eco-tourism and sustainable mobility. Source: VNF, Philéas fotos, Canal du Midi [82].

Based on the taxonomy proposed by Barros et al. [64] and supported by the broader academic literature [1,5,11,27,37,72,79,81,82], the Canal du Midi illustrates how historical infrastructure can be leveraged to address the specific goals of the 2030 Agenda. The canal directly contributes to three SDGs. First, it supports Goal 11 (Sustainable Cities and Communities) by promoting heritage preservation and inclusive access to cultural and green public spaces. Second, it advances Goal 8 (Decent Work and Economic Growth) by generating employment through tourism, maintenance, and environmental management. Third, it aligns with Goal 6 (Clean Water and Sanitation) due to its integration into irrigation and local water regulation systems, particularly relevant in the climate-sensitive Mediterranean region.

In addition, the canal indirectly addresses two further goals. It supports Goal 3 (Good Health and Well-being) by providing car-free recreational routes, enhancing air quality, and promoting active mobility. Finally, Goal 13 (Climate Action) is reflected in the canal's low-carbon tourism model and adaptation strategies in response to environmental stressors such as tree disease and changing hydrological conditions.

The Canal du Midi illustrates how historic inland waterways can evolve into strategic assets for sustainable regional development. Its long-term reuse has supported local economies, safeguarded cultural heritage, and encouraged environmental stewardship. As such, it provides a useful model for integrating ecological, social, and economic dimensions into waterway planning. For future projects, like the Bucharest–Danube Canal, the Midi emphasizes the importance of flexible, multifunctional design and sustained investment in heritage and environmental management.

3.4. Amsterdam–Rhine Canal

The Amsterdam–Rhine Canal is one of the most intensively used inland waterways in Europe, spanning approximately 72 kilometers from the Port of Amsterdam to the

Waal River (a major branch of the Rhine) near Tiel (Figure 9). Officially opened in 1952 and later modernized in the 1980s, the canal links the North Sea to the inland Rhine system, serving as a vital corridor for freight movement in the Netherlands and beyond. By connecting Amsterdam directly to the Rhine basin, the canal has overcome the city's historical disadvantage of lacking direct riverine access, transforming Amsterdam into a fully integrated inland port. The canal now handles around 50–70 million tons of freight per year and sees 83,000 to 100,000 vessel movements annually [85].

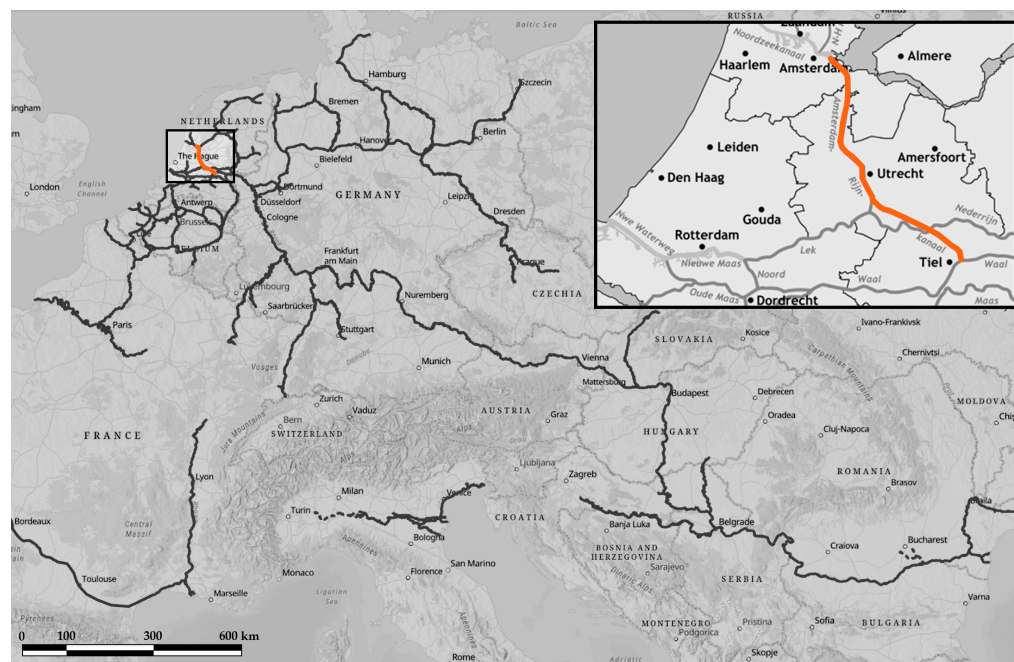


Figure 9. Overview of the Amsterdam–Rhine Canal, linking the Port of Amsterdam to the Waal River near Tiel. Source: authors' compilation based on data from the European Commission TEN-T Regulation [53] and Van Essen [86].

The Amsterdam–Rhine Canal has also stimulated significant economic development along its route, particularly in urban centers such as Utrecht. Its infrastructure enables high-capacity, efficient, and low-emission freight transport, supported by a wide and navigable channel suitable for large vessels (Figure 10), and by several key lock complexes strategically placed along the route [87]. In addition to economic benefits, the canal plays an important role in urban planning, environmental management, and modal shift strategies, offering a strong example of how inland waterways can advance sustainability objectives.

The Amsterdam–Rhine Canal supports substantial freight movement, with volumes growing from approximately 50 million tons in the 1960s to over 70 million tons per year in recent decades [85]. These flows support the logistics needs of major industrial sectors such as petroleum, construction materials, and agribulk commodities. The IWT on this route replaces millions of truck trips, improving energy efficiency and reducing road congestion. According to Rijkswaterstaat [88], vessels on the canal range from single barges to four-unit pushed convoys carrying up to 12,000 tons per trip. Inland shipping emits three to six times less CO₂ per ton-kilometer compared to road freight, translating to an ~80% reduction in emissions [89,90]. The canal's operation thus significantly reduces transport-related CO₂, NO_x, and PM emissions in the region.



Figure 10. Freight transport corridor along the Amsterdam–Rhine Canal.

The Amsterdam–Rhine Canal has become a key economic artery between the Port of Amsterdam and the Rhine basin in Germany. Recent operational and statistical data show how strongly the canal supports employment in several interconnected sectors. Water-linked industrial zones intensify the canal’s labor-market footprint. In 2022, business sites located directly on the Amsterdam–Rhine Canal corridor supported 86,456 jobs, many of which depend wholly or partly on barge or seagoing access [91]. Upstream in Utrecht, the Lage Weide business park, situated on the canal, hosts about 18,000 logistics and manufacturing positions across 800 firms [92]. Infrastructure investment adds another employment layer. A four-year, 33 million-euro maintenance contract awarded in April 2024 for locks and bridges on the Amsterdam–Rhine Canal and in the IJsselmeer region is generating temporary jobs in civil engineering, diving, electro-mechanical repair, and cybersecurity [88].

Labor demand is expected to accelerate during the green transition. Industry estimates indicate that the Dutch inland-shipping sector will need up to 20,000 additional skilled workers by 2030, ranging from skippers to hydrogen-system technicians, to replace retirees and equip vessels with low-emission propulsion. Although freight dominates, tourism still contributes seasonal employment. Before the pandemic, Amsterdam received about 1500 river-cruise calls and nearly 700,000 cruise passengers per year, with numbers increasing in the post-pandemic years as demand rebounded [88,91]. Continuous investments in dredging, lock modernization, and multimodal integration such as rail–barge terminals further enhance the Amsterdam–Rhine Canal’s performance and long-term sustainability.

Based on the taxonomy proposed by Barros et al. [64], and supported by the broader literature [1,5,11,27,37,72,85,87,89,90], the Amsterdam–Rhine Canal makes direct contributions to SDG 9 (Industry, Innovation and Infrastructure) by fostering high-quality, resilient, inland water transport infrastructure. It also contributes to SDG 8 (Decent Work and Economic Growth) by enabling regional economic activity and generating employment in logistics and trade, and to SDG 13 (Climate Action) through its significant reduction in transport emissions via the modal shift from road to water. Indirectly, the canal advances SDG 11 (Sustainable Cities and Communities) by reducing road traffic and improving air quality in urban areas like Amsterdam and Utrecht. It also contributes to SDG 3 (Good Health and Well-being) by mitigating pollution-related health risks and traffic accidents.

The Amsterdam–Rhine Canal exemplifies the strategic role that inland waterways can play in advancing sustainability. It has reinforced Amsterdam’s role as a logistics hub, contributed to regional economic development, and significantly reduced environmental externalities associated with freight transport. The canal’s integration into the Rhine–Alpine

TEN-T Corridor and its capacity for continuous modernization make it a robust model of multimodal, low-carbon infrastructure.

3.5. Correlation of Case Studies with SDGs

The findings highlight the complex and multifaceted contributions of IWT systems to sustainable development, synthesized in Figure 11, which illustrates the relationship between each case study and the six SDGs selected as reference points.

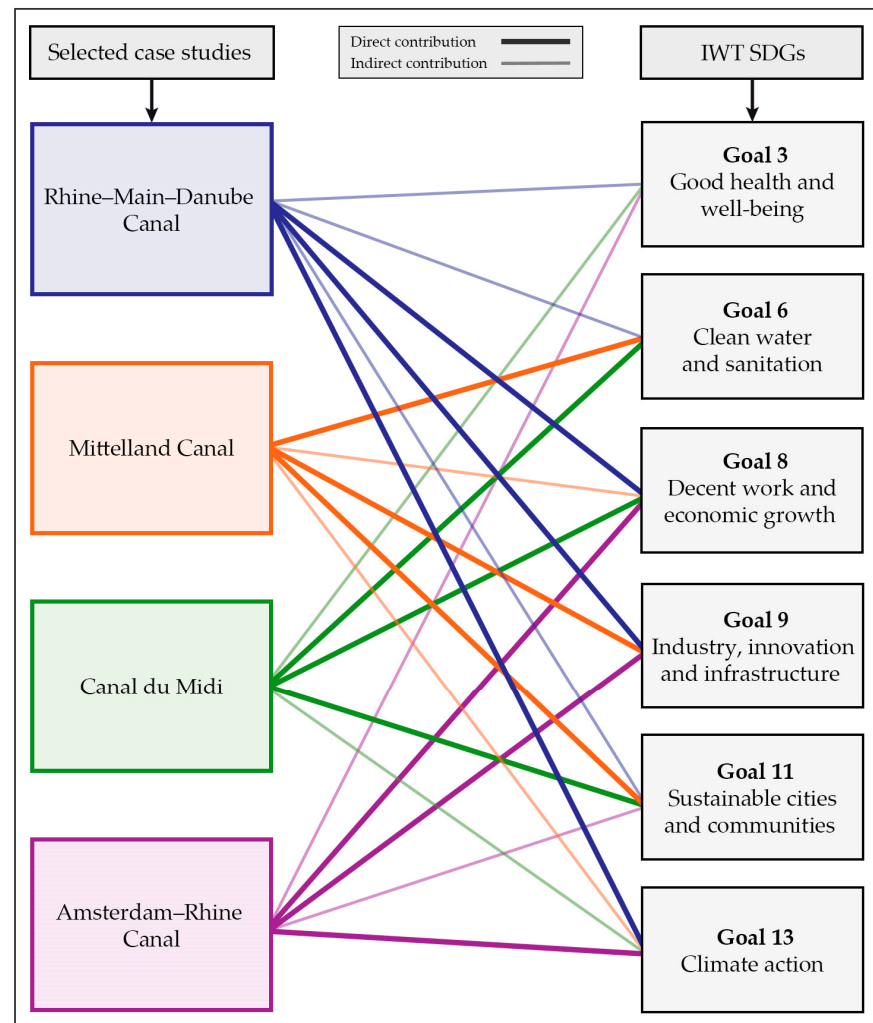


Figure 11. The diagram illustrating both direct and indirect contributions of selected IWT case studies to the SDGs. Source: Authors' work.

Inland waterway transport systems, when strategically embedded within long-term territorial development policies, can play a significant role in advancing sustainable development. The case studies examined in this research demonstrate how such systems contribute to selected SDGs through both their core transport functions and their broader environmental and socio-economic impacts. By identifying direct and indirect forms of contribution, this section offers a structured framework for interpreting the enabling conditions that have allowed similar canal infrastructures to support regional transformation. These insights are particularly valuable for Romania, where the prospective Bucharest–Danube Canal could draw upon these precedents to design an integrated, forward-looking infrastructure aligned with national priorities and European sustainability agendas.

- Goal 3: Good Health and Well-being

Inland waterways contribute to healthier living environments by reducing emissions from road traffic. The Amsterdam–Rhine Canal facilitates the transport of over 70 million tons of freight annually, significantly lowering road-based emissions in urban corridors. Additionally, the Canal du Midi’s replanting initiative—featuring over 19,000 trees and supported by a 200 million-euro ecological restoration program—enhances air quality by sequestering pollutants like PM_{2.5} and NO₂. The green infrastructure also provides recreational space, thereby contributing to public well-being;

- Goal 6: Clean Water and Sanitation

The Rhine–Main–Danube Canal includes flood control structures and links multiple river basins, forming part of an integrated water management network. The Canal du Midi intersects with protected wetlands and support seasonal hydrological regulation. These cases demonstrate how canal infrastructure can play a role in water conservation, irrigation, and sanitary water flow, particularly under conditions of increased drought and hydrological instability;

- Goal 8: Decent Work and Economic Growth

Waterways support a range of employment sectors. The Canal du Midi directly sustains around 2000 jobs and generates approximately 122 million euros annually through tourism, maintenance, and recreational services. The Mittelland Canal supports significant logistics and port activity associated with over 20 million tons of annual freight volume. These figures underline the economic contribution of inland waterways through both freight transport and diversified economic activities;

- Goal 9: Industry, Innovation and Infrastructure

The Rhine–Main–Danube and Amsterdam–Rhine Canals are integrated into major European transport corridors (TEN-T), handling high freight volumes via containerized and multimodal systems. These canals demonstrate the potential for waterways to modernize logistics chains, reduce transport costs, and support resilient infrastructure networks suited to industrial innovation and market expansion;

- Goal 11: Sustainable Cities and Communities

Inland waterways can ease urban traffic loads and support peri-urban development. The Amsterdam–Rhine Canal facilitates urban freight operations that reduce truck traffic in congested areas. The Canal du Midi, with its historic and ecological value, contributes to the creation of culturally enriched and environmentally sustainable communities. The integration of waterways with surrounding urban areas exemplifies their capacity to support sustainable urban planning objectives;

- Goal 13: Climate Action

Shifting freight transport from road to waterways reduces greenhouse gas emissions. The Amsterdam–Rhine Canal has contributed to national modal shift targets, while modernization programs on German canals incorporate climate-adaptive infrastructure and low-emission vessels. These approaches illustrate the role of inland waterways in meeting long-term climate targets through cleaner transport modes and infrastructural resilience.

The comparative insights derived from this evaluation underscore the versatility of inland waterway infrastructure as a policy instrument capable of supporting sustainable development at multiple levels. The case studies examined illustrate how targeted investments in canal systems have generated measurable benefits aligned with international goals. These outcomes serve as a valuable benchmark for Romania, where the Bucharest–Danube Canal remains an unrealized but strategically positioned project. By learning from European precedents and adapting them to local conditions, Romania has the opportunity

to design and implement an infrastructure initiative that not only fulfils transport needs but also addresses broader development challenges in line with the 2030 Agenda.

3.6. Bucharest–Danube Canal: A Prospective Vision

The development of IWT infrastructure must be contextualized not only through sustainability goals but also through spatial asymmetries, multimodal integration, and long-term socio-economic benefits. In this regard, the Bucharest–Danube Canal represents a pivotal opportunity to address historical infrastructural imbalances between eastern and western Europe and to redefine Romania’s position within the transcontinental logistics and transport network.

Inland ports, as critical nodes of multimodal connectivity, combine waterway, road, and rail networks, functioning as both cargo handling points and regional distribution platforms. In recent decades, Danube ports have evolved from conventional shipping terminals into complex logistics hubs. Ports, such as Galați in Romania, Linz in Austria, and Izmail in Ukraine, exemplify this transformation by offering value-added logistics services, regional redistribution, and integration into global supply chains. The Port of Constanța, connected via the Danube–Black Sea Canal, reinforces Romania’s maritime role, serving as a gateway to the Black Sea, Middle East, and Asian markets [93].

The Bucharest–Danube Canal is particularly relevant within this evolving framework. It has been designated as part of the European Union’s TEN-T Core Network and is included in the Rhine–Danube Corridor, reflecting its importance for cross-border integration and intermodal connectivity [94]. By establishing a direct inland navigation route between the Romanian capital and the Danube, the canal would facilitate more efficient freight movement toward the Port of Constanța and enhance Romania’s engagement with European inland waterway systems.

At the national scale, Romania administers approximately 44% of the Danube’s navigable length [95]. However, this strategic advantage has not translated into equivalent infrastructure performance. The prioritization of road and rail investments over IWT has resulted in underutilization of river transport and limited multimodal integration. This imbalance is evident when comparing infrastructure indicators and logistical performance across western and eastern Europe. While countries, such as Austria and Germany, benefit from digitalized terminals, resilient hydrotechnical systems, and container-compatible ports, Romania faces challenges in fully integrating its IWT potential into the wider European transport landscape.

The Romanian context, and particularly the Bucharest–Danube axis, embodies both infrastructural inertia and latent opportunity. Under the 1948 Belgrade Convention [96], Romania plays a critical role in Danube governance; substantial progress was made during the late 20th century to prepare navigational infrastructure along the Argeș and Dâmbovița Rivers. According to the most recent feasibility studies [97], pre-1990 investments exceed 2.7 billion euros. Many of the existing works remain structurally sound yet incomplete; their prolonged abandonment risks irreversible degradation.

To provide a quantitative context for Romania’s inland waterway operations, the table below presents a comparative overview of transport volumes on the Danube and its navigable tributaries in 2017 (Table 2). Romania emerges as the leading country in absolute tonnage, with over 19 million tons of goods transported. This figure includes substantial domestic and international flows; however, the system continues to lag in modal interoperability. The data support the premise that the infrastructural potential of Romania’s IWT sector has yet to be fully realized, and that targeted investments in interconnectivity, such as the Bucharest–Danube Canal, could bridge this performance gap.

Table 2. Transport volume on the Danube and its navigable tributaries in 2017. Source: Eurostat, Statistics Austria [98,99].

Million Tons	DE	AT	SK	HU	HR	BA	RS	RO	BG	MD	UA
Export	0.84	2.40	2.09	3.50	0.19	0.17	2.30	4.21	1.11	0.10	3.67
Import	1.81	4.82	0.10	1.81	0.33	0.09	3.96	5.40	1.73	0.32	0.15
Transit	2.78	1.84	5.01	2.92	5.67	0.00	4.76	2.20	2.20	0.00	0.00
Domestic	0.18	0.39	0.02	0.25	0.06	0.00	1.44	7.32	1.09	0.00	0.01
Total	5.61	9.45	7.22	8.48	6.25	0.26	12.46	19.13	6.13	0.42	3.83

The advancement and completion of the canal project are supported by several critical arguments, as outlined in the updated Environmental Report–Feasibility Study [97]:

- The advanced stage of construction, if left incomplete, is vulnerable to physical degradation caused by vandalism and unmanaged vegetation regrowth;
- The risk of losing previously committed capital investments, amounting to more than 2.7 billion euros;
- The wide array of projected benefits across transport, agriculture, energy, and socio-economic domains.

When operationalized, the canal is expected to deliver high-impact benefits in the following areas:

- Navigation: Establishing a continuous navigable route from Bucharest to the Danube would grant direct access to the European inland waterway network and to the Port of Constanța. This would enhance national freight competitiveness and strengthen Romania’s strategic positioning in Eurasian trade corridors;
- Flood protection: Hydraulic regulation would safeguard over 50,000 hectares of land, protect 11 urban centers, and prevent damage to nearly 10,000 homes, 378 kilometers of road, 5 kilometers of railway, and 126 economic and social infrastructure assets;
- Water supply and irrigation: The canal would enable irrigation over 50,000 hectares and facilitate drainage on an additional 30,000 hectares. It would also support aquaculture on 1250 hectares and provide water supply infrastructure for nearby communities;
- Renewable energy: The hydropower component is expected to generate approximately 126 GWh per year, contributing to national energy targets and reducing dependence on fossil fuels;
- Employment and local development: The canal is projected to generate more than 21,000 jobs during the construction phase and sustain 520 permanent positions thereafter. It is also expected to attract investments in logistics hubs, industrial parks, and tourism infrastructure, catalyzing regional growth and reducing spatial disparities.

These multifunctional benefits confirm that the Bucharest–Danube Canal transcends its role as a transport corridor. It must be understood as an integrated development axis that can foster regional cohesion, environmental resilience, and economic diversification. Its contribution to national objectives—ranging from climate mitigation and territorial equity to connectivity and industrial transformation—aligns with broader European visions for green and inclusive growth.

4. Discussion

This research demonstrates that IWT systems, when embedded in coherent territorial development strategies, can advance sustainability objectives through an integrated combination of spatial functionality, environmental performance, and socio-economic utility. The

case studies selected for analysis have not only offered comparative perspectives, but also enabled the identification of structural, operational, and governance-related factors that facilitate successful implementation across diverse contexts. These insights have proven particularly valuable in generating an informed framework for interpreting the potential of the Bucharest–Danube Canal.

Within this analytical framework, the Bucharest–Danube Canal project remains one of Romania’s most significant, yet underutilized, infrastructure opportunities. Despite decades of partial implementation, its strategic potential continues to be relevant in the context of national and European transport planning. It has the capacity to improve regional connectivity, stimulate economic development, reduce environmental pressures, and contribute to climate adaptation objectives.

The project’s multifunctional character enhances its strategic value. As a transportation corridor, it would provide direct navigable access between Bucharest and the Danube, strengthening the capital’s connectivity to the Port of Constanța and to broader European trade flows.

As a water management system, it would improve flood protection for vulnerable settlements, secure water supply for agriculture and local communities, and support irrigation and drainage on tens of thousands of hectares of arable land. From an energy perspective, the canal’s infrastructure is expected to support the generation of renewable energy through hydropower, with an estimated production capacity of 126 GWh annually. These functions are further complemented by the potential for job creation, both during the construction and operational phases, contributing to regional economic resilience and social inclusion.

However, the development process has faced limitations that must be acknowledged. Delays have largely stemmed from institutional fragmentation, inconsistent political support, and a lack of integrated planning frameworks. At the same time, the core structure of the canal and the investments already made offer a strong foundation for further development. The advanced stage of construction works, the alignment with European transport corridors, and the projected multifunctional benefits position the canal as a viable and impactful infrastructure.

Coordinating sustainable development in the future will require a shift toward integrated governance, cross-sectoral collaboration, and updated technical and environmental assessments. In essence, the canal must be reframed not as a stalled infrastructural relic but as a forward-looking platform for regional transformation. Its development should not be approached in isolation but as part of a broader territorial strategy that balances economic growth, environmental sustainability, and social equity. When viewed through this lens, the Bucharest–Danube Canal represents not only an opportunity for Romania to modernize its IWT sector, but also a pathway toward a more integrated and resilient spatial development model within the European context.

5. Conclusions

This research has analyzed the strategic role of IWT in advancing sustainability objectives, with a particular emphasis on the prospective development of the Bucharest–Danube Canal. By adopting a spatially integrated and case-informed methodology, the study has demonstrated that inland waterways, when embedded in comprehensive territorial planning, can serve as catalysts for economic diversification, environmental regeneration, and regional cohesion.

The inclusion of comparative European case studies has enriched the analytical framework, offering valuable insights into the conditions under which inland waterway systems become effective instruments for sustainable development. These cases have contributed

to identifying principles that are transferable to the Romanian context, helping to clarify how intermodal integration, institutional coordination, and multifunctionality can be operationalized in infrastructure planning.

Within this perspective, the Bucharest–Danube Canal emerges not only as a project of national interest, but also as a pivotal intervention capable of aligning Romania’s development trajectory with broader European sustainability agendas. Its capacity to support freight mobility, irrigation, energy production, flood protection, and job creation reinforces its multifunctional profile and long-term value.

To realize this potential, a renewed strategic vision is required, one that emphasizes coherent policy alignment, inclusive governance structures, and sustained investment efforts. The Bucharest–Danube Canal project offers Romania a timely opportunity to reposition IWT as a cornerstone of balanced, climate-resilient, and future-oriented territorial development.

Author Contributions: All authors (G.-G.L., D.-I.G. and L.C.) made equal contributions to the preparation of this scientific paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are included in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IWT	Inland Waterway Transport
SDGs	Sustainable Development Goals
TEN-T	Trans-European Transport Network
EU	European Union

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