

Article

Unlocking the Potential of Inland Waterway Transport: An Expert-Approved Infrastructure Index Designed for Regional Ports

Vilma Locaitienė¹ and Kristina Čižiūnienė^{2,*}

¹ Department of Port Engineering, Lithuanian Maritime Academy, Vilnius Gediminas Technical University, I. Kanto Str. 7, 92123 Klaipėda, Lithuania; vilma.locaitiene@vilniustech.lt

² Department of Logistics and Transport Management, Faculty of Transport Engineering, Vilnius Gediminas Technical University, Plytinės Str. 25, 10105 Vilnius, Lithuania

* Correspondence: kristina.ciziuniene@vilniustech.lt

Abstract

Even though the literature extensively examines aspects of the efficiency, waterway infrastructure, and competitiveness of inland waterway transport (IWT), a systemic composite index that integrates navigational, operational, and digital factors of IWT infrastructure into a single comparable evaluation system at the level of port hinterlands has not been identified. This study proposes a multi-criteria inland waterway transport infrastructure index (IWTI) designed to assess complex infrastructure conditions. The IWTI measures infrastructural readiness, physical navigational, operational, and digital prerequisites that enable the realisation of IWT potential. The index is calculated using the multi-criteria decision-making method TOPSIS, with criterion weights determined based on expert evaluation ($n = 7$) data. Rank stability was tested via Spearman's rank correlation sensitivity analysis under three alternative weighting scenarios. The methodology was applied to assess seven ports in the Baltic Sea region using data from 2023. The IWTI ranges from 0.00 (Tallinn does not have an IWT connection) to 0.80 (Szczecin). The study revealed significant regional differences: the hinterland of the HaminaKotka port is characterised by a mature Saimaa canal and lake system; the hinterlands of Szczecin and Klaipėda demonstrate strong potential for the Oder/Odra and Nemunas corridors; the port of Gdańsk was identified as a medium-potential case with clearly defined priorities for infrastructure improvements. The ports of Gdynia and Riga lack functional inland waterway connections, but the infrastructural potential scenario indicates significant IWTI growth opportunities upon the implementation of planned investments. Sensitivity analysis confirmed high stability of the rank (Spearman $\rho \geq 0.964$ in all scenarios). The proposed index provides a structured methodological basis for evaluating IWT potential and can serve as a decision-making tool for infrastructure planning and transport policy development, contributing to sustainable cargo carriage and the decarbonisation goals of the transport sector.



Academic Editor: Meng Guo

Received: 8 May 2026

Revised: 9 June 2026

Accepted: 15 June 2026

Published: 18 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: inland waterway transport; sustainable transport; infrastructure assessment; composite index; TOPSIS; Baltic Sea region ports

1. Introduction

The sustainable development of the transport sector remains one of the key priorities of the European Union's climate policy. The European Green Deal and the Sustainable and Smart Mobility Strategy set the goal of reducing greenhouse gas emissions from the

transport sector by 90% by 2050, a target achievable only by harnessing the potential of all modes of transport [1]. The latest guidelines from the European Commission, the EU Industrial Maritime Strategy (COM(2026) 111 final), further emphasise the need to increase the role of low-carbon transport modes—particularly railways and inland waterway transport—by enhancing their infrastructural preparedness, digitalisation, and integration into the TEN-T network [2]. In this context, inland waterway transport (IWT) is considered one of the most environmentally efficient cargo transport alternatives, characterised by lower emissions and higher energy efficiency. Compared to road transport, IWT consumes approximately 17% less fuel per tonne in cargo transport [3,4]. However, despite these advantages, the modal share of IWT in the European Union remains very small, about 1.7% in tonne-kilometres, whereas road transport accounts for more than 70% of all cargo carriage [5].

To enhance the significance of IWT within the transport system, the European Commission approved the NAIADES III action plan (2021–2027) in 2021 [1], which aims to increase the volume of inland waterways and short sea shipping transport by 25% by 2030 and by 50% by 2050. These initiatives focus on infrastructure modernisation, sector digitalisation, and the transition to a zero-emission fleet. Although political objectives are formulated at the EU level, their implementation at the regional level faces challenges due to the lack of methodological assessment tools, particularly in regions with specific geographical and hydrological conditions.

In the Baltic Sea region, this gap between strategic objectives and practical implementation is particularly evident. Countries in the region, such as Lithuania, Latvia, Estonia, Poland, and Finland, possess inland waterways potentially suitable for navigation (the basins of the Nemunas, Vistula, and Daugava rivers, the Saimaa canal and lake system), which could be integrated into port hinterland transport systems. However, the actual integration of IWT remains minimal: in many of these countries, the share of inland waterway transport is insignificant or not statistically recorded [5,6]. The transport system is dominated by road, rail, and maritime transport, while IWT remains structurally underutilised.

The scientific literature examines various aspects of IWT, including sustainability, development barriers, competitiveness, and intermodal integration [3,7–10]. Composite indices, such as the Liner Shipping Connectivity Index (LSCI), Container Port Performance Index (CPPI), and Sustainable Inland Transport Connectivity Indicators (SITCIN), are used to assess transport system efficiency and connectivity. However, these indices focus on maritime transport, operational efficiency, or overall transport system connectivity and do not address inland waterway infrastructure readiness as a separate evaluation object. Furthermore, the literature does not provide for any composite index combining infrastructural, operational, and digital factors into a unified assessment system for inland waterway transport infrastructure at the port hinterland level.

Given this identified methodological gap, the aim of this study is to develop a multi-criteria inland waterway transport infrastructure index (IWTI) for assessing infrastructural conditions for IWT development in the hinterlands of Baltic Sea region ports. The index consists of five sub-indicators that evaluate technical navigability (CEMT classification), operational stability (depth reliability), time accessibility (seasonal restrictions), digital infrastructure (RIS coverage), and inland terminal capacities.

The study focuses on the eastern Baltic Sea region because inland waterway transport in this area differs substantially from the mature systems of Western Europe. Belgium, the Netherlands, Germany, France and the Danube basin countries have long-established inland waterway networks, higher navigational parameters and stable cargo flows. These conditions are not directly comparable with the eastern Baltic ports, where inland waterway transport remains less developed and only partly integrated into port hinterland systems.

In the analysed region, higher cargo flows are mainly observed in Finland, partly due to coastal and inter-island navigation, and along the Oder/Odra corridor. Therefore, the IWTI is developed as a tool for assessing regions where inland waterway potential exists, but infrastructure and operational readiness remain uneven.

Sub-indicator weights are determined based on expert evaluation, while aggregation is performed using the TOPSIS method. The methodology is empirically applied to seven Baltic Sea region ports using data from 2023.

The proposed IWTI focuses on potential rather than actual transport flows. It assesses the technical, hydrographic, and operational conditions that enable IWT development, given appropriate investments and policy measures. The choice to evaluate from the supply side is grounded in the fact that actual IWT flows in the Baltic Sea region are low and do not allow differentiation of ports based on their structural potential. The proposed IWTI can clearly distinguish ports where IWT development is structurally constrained from those with real development opportunities.

The scientific contribution of this study can be assessed in three directions. First, a new empirically based and reproducible assessment index for inland waterway transport infrastructure is created. Second, by applying the TOPSIS method with expert-defined weights, the transparency and methodological soundness of the evaluation process are ensured. Third, the empirical results enable the identification of regional infrastructure development priorities and provide a foundation for decision-making related to investment planning and the development of the TEN-T network.

The article consists of several parts: Section 2 provides a literature review; Section 3 describes the structure of the IWTI, the specification of dimensions, and the expert evaluation methodology, also listing the TOPSIS aggregation procedure; Section 4 presents the results of the empirical application and sensitivity analysis; Section 5 discusses opportunities for further research, while Section 6 provides conclusions.

2. Literature Review

2.1. Connectivity of Maritime Port Hinterlands and Limitations to Inland Waterway Transport Development

The interaction between port competitiveness and hinterland transport systems is conceptualised in the scientific literature through the prism of port regionalisation [11,12]. This concept emphasises that the competitiveness of a modern regional maritime port depends not only on the parameters of the port's water gateway access but also on the level of integration of IWTC in the hinterland zone. A port operates as a node within a broader regional logistics network, while its hinterland is not a statically defined geographical area but a dynamically changing cargo flow field shaped by market conditions, the competitiveness of transport modes, and infrastructural readiness [13,14]. The quality of transport connections—both maritime and inland—directly determines the spatial extent of a port's hinterland and its ability to serve a broader economic zone [15]. Research shows that intermodal connections (railways and inland waterways) significantly reduce the distance barrier for cargo owners when choosing a port [14]. In this context, intermodal hinterland connections determine port accessibility and its role in the regional logistics chain [12,16,17].

The sustainability of hinterland transport is an increasingly relevant topic in policy and scientific research. Hinterland transport associated with ports significantly contributes to negative external impacts across the logistics chain, such as greenhouse gas emissions, congestion, and traffic safety issues [18,19]. Research indicates that modal shift policy measures—pricing, increasing rail capacity, and subsidies—can significantly reduce transport external costs, although their effectiveness depends on a comprehensive combination

of measures rather than isolated solutions [19]. Research based on simulation scenarios confirms that infrastructure development and improvements in operational efficiency, combined with modal shift measures, can significantly reduce CO₂ emissions in port hinterland transport systems [20].

IWTCs are theoretically considered one of the most efficient and sustainable components of hinterland connectivity due to lower emissions and high cargo capacity compared to road and rail transport [21–23]. However, despite these advantages, IWTC development faces significant structural, technical, and operational constraints that limit its integration into hinterland logistics chains. Studies indicate that the main limiting factors include insufficient navigational channel depth, limited lock capacity, infrastructure degradation, and insufficient integration into intermodal transport chains [6,24,25].

Hydrological and climatic factors, such as water level fluctuations, speed of the current, and seasonal ice phenomena, are becoming increasingly more important due to climate change, directly affecting shipping reliability and cargo delivery planning [26,27].

In this context, the Baltic Sea region stands out as one of the least developed IWTC application regions in Europe. Although rivers such as the Nemunas, Vistula, and Daugava have the potential to be integrated into port hinterland transport systems, their practical utilisation remains limited [3,28]. Scientific research highlights a lack of both infrastructural solutions and systematic planning to effectively exploit the potential of inland waterways in this region.

This underutilisation of infrastructural capacity is conceptualised as a structural modal reserve—a physically existing but untapped connectivity potential due to institutional, technical, and infrastructural barriers [23,28,29]. Therefore, assessing IWTC infrastructure potential at the port hinterland level is not only a technical task but also a strategic one that is directly linked to the decarbonisation opportunities of the region's transport system.

2.2. IWT Infrastructure Factors and Their Significance for Port Hinterland Connectivity

Infrastructure and technology are among the critical barriers to IWTC development [30]. This group of factors includes physical navigational constraints of inland waterways and structural delays in the implementation of technological innovations.

Physical infrastructure constraints create so-called “bottlenecks” that limit navigation and waterway capacity, affecting the economic efficiency of IWTC utilisation. Critical technical parameters include the physical characteristics of waterways and infrastructure, such as river depth, channel width, bridge clearance, lock dimensions, and quay infrastructure (Table 1).

Table 1. Technical IWTC infrastructure parameters.

Parameter	Description	Authors
Vessel dimensions	Length, width, draught, and turning radius	[24,31–35]
Vessel capacity (DWT)	The amount of cargo carried, the required reserves, and the scope of the necessary reserves	[9,36–38]
River channel depths	Average and minimum depth during critical seasons (e.g., droughts)	[9,24,27,33,35,37]
Waterway width	Capacity and ability for two-way shipping traffic	[31,33,36,37,39]
Bridge clearance	Height limitations for cargo vessels	[9,33,34,37]
Lock size and location	Restrictive factor for traffic flow and permissible vessel dimensions	[33,37,40,41]
Quay infrastructure and maintenance level	Handling points, limitations on navigable rivers, and regular dredging and assurance of technical waterway maintenance	[9,23,25,42]

Source: Compiled by the authors based on the data provided in the specified sources.

The main parameters of the IWT infrastructure, summarised in Table 1, determine whether certain classes of vessels can be safely and efficiently operated on waterways. One critical parameter is the depth of the river fairway, which determines the permissible draught of the vessel and, consequently, its cargo capacity [24,35]. Insufficient depth reduces the efficiency of voyages and increases per-unit transportation costs [43]. Another limiting factor is the height of bridges, which restricts the number of container tiers transported by barges and reduces the competitiveness of IWT, especially compared to road and rail transport. Narrow canals or navigation segments with limited width reduce capacity and increase the risk of delays in IWT.

The technical parameters of IWT infrastructure in Europe are standardised based on the classification established by CEMT (Conférence Européenne des Ministres des Transports). This classification defines European waterway classes (I–VII), specifying permissible vessel sizes and minimum infrastructure standards, including fairway depth, lock dimensions, and bridge clearance [33,37]. The CEMT classification serves as the primary technical reference for assessing inland waterway infrastructure in Europe.

CEMT classification parameters do not have the same practical meaning across all European regions. In Germany, France and the Netherlands, many inland waterways belong to higher CEMT classes, often Class Va–VII, and operate within more developed lock systems and more stable navigability conditions. This supports regular use of large push convoys and container barges.

The eastern Baltic Sea region has a different profile. Its waterways are mainly Class II–IV and are more exposed to seasonal water-level changes, ice conditions and limited lock infrastructure. Therefore, depth reliability, seasonal restrictions and lock availability are not merely operational parameters. In this regional context, they are core infrastructure constraints for IWT development.

In addition to physical infrastructure parameters, the reliability of IWT is influenced by navigational factors such as water level fluctuations, current speed, and seasonal restrictions. These factors directly impact navigation times and the reliability of cargo deliveries. The Baltic region is particularly characterised by significant hydrological variability and specific ice conditions, which limit the duration of the navigation season [26,27]. Infrastructure measures can partially mitigate these limitations. For example, the case of Finland’s Saimaa Canal system demonstrates that the use of icebreakers extends the navigation season and enhances operational reliability [44].

Another group of factors consists of technological factors such as energy transformation, digitalisation, and automation processes. These processes are identified as essential elements that enhance the efficiency and competitiveness of inland water transport (IWT) [30,45,46]. Their development is directly linked to the sector’s ability to adapt to decarbonisation targets and implement digital logistics solutions.

Energy transformation in the IWT sector is manifested through the technological development of vessels and ports, covering vessel engine types, fuel consumption, and their energy efficiency. This group includes solutions that can significantly reduce emissions during cargo handling operations in ports serving IWT. Higher energy efficiency and lower total emissions increase the appeal of logistics chains based on IWT [14,21].

Special attention is given to digital technologies. The river information services (RIS) directive (2005/44/EC) established the legal framework for the implementation of digital navigation management systems on European waterways of Class IV and above, integrating vessel tracking, lock planning, and water level monitoring functions into a unified digital platform [47–53]. The development of these systems is considered an important indicator of the modernisation and competitiveness of the inland waterway transport system [54,55].

Alongside the implementation of RIS systems, the operational systems of port terminals are being integrated into shared digital platforms. Integrated digital systems create the conditions for real-time shipment tracking and the utilisation of synchro-modal opportunities in combined maritime, inland waterway, and road transport chains [52,56,57]. Recent studies on digital information in maritime supply chains also emphasise the importance of information sharing for supply chain management. Cloud-based platforms and blockchain-enabled solutions can increase transparency, improve information-sharing capabilities and support coordination in complex maritime logistics networks. These digital enablers are also relevant for integrated maritime, inland waterway and road transport chains, where real-time information exchange is required for synchro-modal operations [58]. This development is complemented by the European Commission's NAIADES III initiative. One of its two main objectives is the comprehensive digitalisation of the sector, including the expansion of RIS network management at the EU level, the creation of a unified data space, and the establishment of regulatory frameworks for autonomous navigation [59].

Table 2 lists the most frequently discussed technological parameters.

Table 2. Technological IWT infrastructure parameters.

Parameter	Description	Authors
River vessel engines and energy	The impact of engine type, power, and energy efficiency indices (EEDI, EEOI) on cargo transportation costs and environmental impact	[21,22,60]
Fuel consumption and alternative fuels	Fuel consumption per tonne transported; the potential of alternative fuels (LNG, hydrogen, electric engines) to reduce emissions	[4,22,60,61]
Digital navigation management infrastructure (RIS/AIS)	River information services (RIS) as integrated shore infrastructure—vessel tracking (AIS), lock planning, water level monitoring, and traffic management; radar equipment as a component of vessel-level digital integration	[33,47,48,50,53,54]
Cargo terminal handling performance	Intensity of cargo handling operations (tonnes/hour); the level of terminal mechanisation and automation as a factor of IWT competitiveness	[15,23,25,62]
Compatibility with other transport modes during cargo handling	Technological and infrastructural compatibility between river ports and road and rail terminals—standardisation of cargo units (containers, storage units, RO-RO) as a prerequisite for forming intermodal and synchro-modal transport chains	[16,23,30,42,46,56,62]
River port capacity	Annual handling capacity (million tonnes/year); port infrastructure compliance with AGN minimum standards (0.5 million tonnes/year)	[25,45,46,63]

Source: Compiled by the authors based on the data provided in the specified sources.

The technological parameters (Table 2) encompass both the efficiency dimensions of the river fleet and the characteristics of digital infrastructure and terminal operational capacity, which together determine the level of modernisation of the IWT system and its ability to integrate into intermodal cargo transport chains.

Although the energy efficiency and fuel consumption parameters of the river fleet (Table 2) are important in the context of IWT decarbonisation, they are not included in the calculation of the IWTI in this study. Energy indicators characterise the technological maturity of the fleet [22] rather than infrastructural readiness; that is, they reflect the current operational situation rather than the structural prerequisites that determine whether IWT is feasible in a specific corridor. On the other hand, these parameters measure how efficiently the existing vehicles are utilised rather than the infrastructural conditions that create the

prerequisites for transport development. The IWTI is based on a supply-side perspective, focusing on physical, navigational, and digital infrastructure prerequisites, which are necessary, though insufficient, conditions for modal shifts [9,12,14].

The analysis of the technical and technological parameters of IWT infrastructure forms an important theoretical basis for the evaluation of IWT. Most studies are limited to the analysis of individual factors and do not provide an integrated evaluation model that allows for a comprehensive assessment of infrastructural potential. In light of this, there is a need to apply systemic evaluation methods that enable the integration of various infrastructural and technological factors into a unified analytical framework. From this perspective, composite indices become an appropriate methodological tool, allowing for the aggregation of different indicators, the assessment of their interrelations, and the comparison of readiness levels across different regions or transport corridors.

2.3. Methodological Principles for Creating Composite Indices and Their Application to IWT Evaluation

Composite indices are widely used in the evaluation of transport and logistics systems to summarise multidimensional characteristics into a single integrated indicator, enabling comparative analysis between different objects, regions, or periods.

The Liner Shipping Connectivity Index (LSCI) evaluates the integration of countries into global maritime transport networks based on the number of shipping lines, vessel capacity, and service frequency. It operates at the national level but does not include the hinterland level of the port [64]. The Container Port Performance Index (CPPI) focuses on port operational efficiency and time consumption analysis [65]. It relies on actual ship servicing data but does not encompass physical infrastructure parameters. Both indices are oriented towards maritime transport indicators and do not account for the infrastructural readiness of inland waterways.

The United Nations Economic Commission for Europe (UNECE) developed the Sustainable Inland Transport Connectivity Indicators (SITCIN), which is the most comprehensive existing evaluation tool for inland transport systems, covering 215 indicators for assessing road, rail, inland waterway, and intermodal transport systems [66]. SITCIN is structured around the three pillars of sustainability—economic, social, and environmental—and is oriented towards monitoring countries' progress in achieving transport-related sustainable development goals [67]. SITCIN's inland water transport indicators include infrastructure compliance with international standards, RIS coverage, the quality of terminal connectivity with road and rail networks, and the actual share of cargo transported via inland waterways [66].

However, the application of SITCIN in this context has significant limitations. SITCIN is a national-level instrument primarily designed for developing and landlocked countries [67]. It focuses on legal compliance and actual operational indicators, i.e., the current state of the system, rather than infrastructural potential. Such an approach is not suitable for the context of the Baltic Sea basin rivers, where actual IWT flows are uniformly low across almost all ports with potentially suitable waterways. SITCIN does not include indicators for navigational depth reliability or seasonal accessibility, which directly limit the duration of the navigation season and vessel utilisation opportunities in the Baltic basin. Furthermore, SITCIN's unit of analysis is a country rather than a port or hinterland transport corridor, thus it does not provide the necessary differentiation to determine investment priorities at the port level.

The methodological principles for creating composite indices are extensively discussed both in the academic literature and in the methodological guidelines prepared by international organisations. One of the main sources is the Handbook on Constructing Composite Indicators, which defines the creation of composite indices as a sequential multi-

step process involving conceptual model justification, indicator selection, data processing, normalisation, weighting, and aggregation [68].

Ayadi et al. (2024) conducted a comprehensive systematic review of 47 transport sustainability assessment indices, which highlights that the choice of normalisation, weighting, and aggregation methods significantly affects the final index result [69].

Other composite indices, such as the Water Poverty Index (WPI) or Human Development Index (HDI), are methodologically important as they demonstrate how different dimensions can be integrated into a single aggregated indicator [69–71]. The principles of creating these indices, namely, indicator normalisation, weighting, and aggregation [68], are widely applied in developing transport infrastructure assessment models.

The key methodological dilemma in creating composite indices is the choice of the aggregation method for the indicators constituting the index. Simple weighted summation allows for compensation between criteria [71], but this may be problematic when assessing infrastructure dimensions that are structurally non-substitutable. For example, a high score for RIS coverage cannot physically compensate for insufficient navigational depth when evaluating IWT potential. In this context, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is considered a more suitable choice because it assesses the proximity of each alternative to both the positive ideal and negative ideal solution based on multiple criteria simultaneously [72]. TOPSIS was therefore selected not as a non-compensatory method, but as a distance-based MCDM approach that enables the ranking of composite infrastructure profiles while keeping the positive ideal and negative ideal reference points explicit.

The application of the TOPSIS method in the inland waterway transport sector is not new. Liu et al. (2016) applied this method to evaluate inland waterway navigational safety and demonstrated that TOPSIS is suitable for analysing systems with diverse evaluation criteria [73]. This is particularly important when assessing IWT infrastructure, which consists of various parameters that are non-substitutable and cannot partially compensate for one another, requiring a comprehensive evaluation. TOPSIS is widely used in transport infrastructure and port evaluation studies. Mardani et al. (2016) highlighted its application in more than 300 multi-criteria decision-making (MCDM) studies in the transport sector, including its suitability when making complex infrastructure decisions [74].

Indices evaluating the potential of the infrastructure conceptually differ from operational efficiency indicators in terms of their evaluation perspective. Supply-side indices measure infrastructural prerequisites that enable transport development regardless of the current level of flows, while demand-side indices assess the actual utilisation of the system [12,43]. Supply-side indices, particularly relevant in regions where actual transport flows are low, are not due to a lack of physical infrastructure but because of structural barriers. This is precisely the situation of IWT in the Baltic Sea region identified in this study.

In summary, the analysis of the literature suggests that the potential of IWT infrastructure is most often evaluated in a fragmented manner, focusing on individual technical, navigational, or technological factors. Although these factors are well-identified (Section 2.2), they are not integrated into a single evaluation system that would allow for a comparative analysis of different ports. The existing transport indices, such as LSCI, CPPI, or SITCIN, are oriented towards maritime transport, operational efficiency, or national-level connectivity, but do not address the infrastructural prerequisites that determine IWT development opportunities at the hinterland level of ports. A clear methodological gap remains: the absence of a composite, multi-criteria index based on a supply-side perspective and expert-validated weights, designed to evaluate the level of IWT infrastructural readiness in the hinterlands of regional seaports. In view of this, the study proposes the inland waterway transport infrastructure index (IWTI), which integrates technical, navigational,

and digital factors into a unified evaluation system, enabling a comparative assessment of regional ports' IWT infrastructure and helping to identify development priorities.

3. Data and Methods

3.1. Study Sample

The study focuses on ports located along the eastern Baltic Sea coast (Gdańsk, Gdynia, Szczecin, Klaipėda, Riga, HaminaKotka, Tallinn). Unlike Western Europe (Rotterdam, Antwerp, Amsterdam), where 15–35% of cargo flows are redistributed via IWT [5], barge carriage in the eastern Baltic region can be considered a latent opportunity. The study adopts a potential evaluation approach rather than assessing actual flows, measuring infrastructural capacity as an initial condition for modal shift.

The seven ports were selected to ensure cross-national comparability within a structurally coherent regional setting. The group of Baltic Sea coastal ports was selected as an analytically homogeneous sample based on three key criteria:

- Hydroclimatic Coherence: Limited navigation distance (<300 km from the seaport), similar seasonality (210–330 days), and identical river hydrological variability (ice regime, water level fluctuations).
- Hinterland Market Structure: The ports serve transit corridors in Central and Eastern Europe, characterised by similar cargo generation dynamics.
- Legal and Political Regulation: A common EU TEN-T network strategy and unified EU directives related to the decarbonisation of the transport sector.

Such a sample allows for the identification of structural conditions under which IWT could become a significant part of the regional logistics system, shifting cargo flows from road transport and reducing the emission intensity of transport chains.

Three analytically distinct port categories are identified within the sample: (1) ports with functioning or historically documented IWT corridors, namely, Gdańsk (E40/E70, Visla basin), Klaipėda (E41, Nemunas), Szczecin (E30, Odra), AND HaminaKotka (via the Saimaa lakes and canal system, connected by the Saimaa Canal); (2) ports without IWT connections due to geographical constraints; AND (3) the case of Riga port, with the Daugava river crossing it. The Daugava has documented AGN classification-compliant potential but remains blocked by three hydroelectric dams that do not have navigation locks. The Riga case was selected to evaluate an intermediate category where IWT development is restricted by infrastructural barriers rather than geographical limitations and is accordingly assessed in sensitivity analysis.

Based on the presented characteristics of the hinterlands of the studied ports, the structure of the IWTI and the calculation methodology for each dimension, grounded in a specific set of sub-indicators, is further elaborated.

3.2. Composite IWT Index: Structure and Sub-Indicators

The inland waterway transport infrastructure index (IWTI) is a composite supply-side indicator designed to evaluate the infrastructural conditions for integrating inland waterway transport (IWT) into port hinterland logistics. The index combines five sub-indicators (I_1 – I_5) that cover the physical, operational, digital, and logistical dimensions of inland waterway infrastructure (Figure 1).

Figure 1 presents the five-dimensional structure of the IWTI. I_1 and I_2 capture the core navigability conditions of the corridor, while I_3 , I_4 and I_5 reflect seasonal accessibility, digital navigation support and terminal handling capacity. Together, these sub-indicators form the composite infrastructure profile used for the TOPSIS-based ranking. Each sub-indicator is defined to reflect a structurally distinct and non-substitutable dimension. Before TOPSIS aggregation, all indicators are normalised to a common [0; 1] scale.

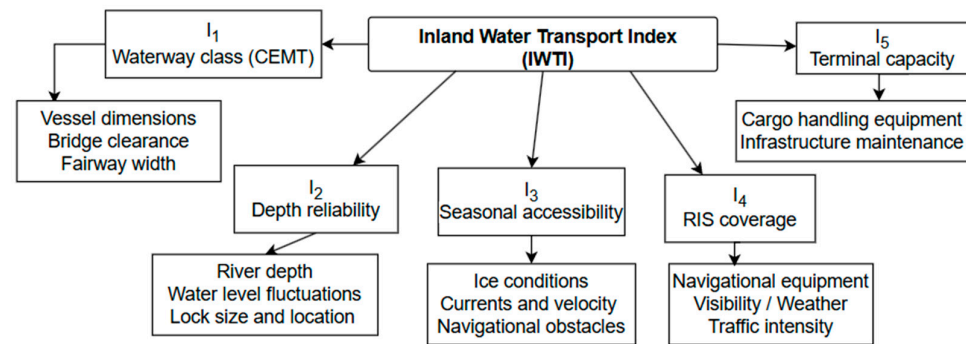


Figure 1. Structure of the composite IWTI. Source: Compiled by the authors.

Sub-indicator I_1 (CEMT class) measures the structural technical capacity of the inland waterway corridor, considering characteristics such as width, depth, number of locks, etc. As these characteristics may vary across different segments of the inland waterway corridor, a weighted average of the CEMT classes for all segments is calculated according to Formula (1):

$$I_1 = \frac{\sum_{i=1}^N CEMT_i \times L_i}{\sum_{i=1}^N L_i}, \quad (1)$$

where i is an individual segment of the waterway, N is the total number of waterway segments, $CEMT_i$ is the numerical value of the international inland waterway class for the segment (Class I represents 1 point, etc.), and L_i is the length of the segment in kilometres.

The basis for the CEMT classification is the UNECE Blue Book (4th edition, 2024 and the data of Annex I to the AGN agreement (Table 3).

Table 3. Maximum vessel dimensions according to CEMT (1992).

CEMT Class	Type of Motor Vessel and Barges	Maximum Characteristics (Length (L), Beam (B), Draught (D))	Tonnage, (t)	Minimum Height Under Bridges, (m)
I	Spits, barges	L: 38.5 m, B: 5.05 m, D: 1.8 m	250–400	4.00
II	Kempenaar class	L: 50–55 m, B: 6.6 m, D: 1.8 m	400–650	4.00
III	Gustav Koenigs	L: 67–80 m, B: 8.2 m, D: 1.8 m	650–1000	4.00
IV	Johann Welker	L: 80–85 m, B: 9.5 m, D: 2.5 m	1000–1500	5.25
Va	Large Rhine vessel	L: 95–110 m, B: 11.4 m, D: 2.8 m	1500–3000	5.25
Vb	Pushed convoy 2 ×	L: 172–185 m, B: 11.4 m, D: 2.8 m	3200–6000	5.25
VIa	Pushed convoy 2 × 2	L: 95–110 m, B: 22.8 m, D: 2.8 m	3200–6000	7.00
VIIb	Rhine-class 2 × 4	L: 110–195 m, B: 22.8–33 m, D: 2.8–4.5 m	6400–12,000	9.10

Source: Compiled by the authors based on the data provided in the specified sources [37,38].

The technical parameters of Class I–III waterways are determined by national legislation, as these waterways are classified as regionally significant inland waterways. The specified minimum bridge height includes a safety clearance of approximately 0.30 m between the highest point of the vessel's structure or cargo and the bridge structure to ensure safe navigation. Empirical estimates indicate that container transportation by barges requires a minimum height of 5.25 m for a two-tier carriage, approximately 7.0 m for three-tier transportation, and approximately 9.10 m for a four-tier carriage [38].

The permissible vessel draught for a specific inland waterway is determined based on local hydrological and morphological conditions and may vary significantly between different sections. In some sections of Class VII waterways, convoys consisting of a larger number of barges are permitted. In such cases, the horizontal dimensions of the convoys may exceed the upper limits specified in standard classifications [75]. In other sections, locks

are in operation, which again restrict navigation [40]. All such cases must be considered when planning infrastructure capacity and organising navigation.

CEMT classification data are obtained from the official UNECE E-waterway website. Each segment is assigned a specific CEMT class, which is factored into the overall corridor evaluation.

The reliability of waterway depth (I_2) is defined as the number of months during which the minimum fairway depth is guaranteed. Although the AGN Agreement [38] provides for a minimum depth of 2.50 m for international E-class inland waterways, specific regional infrastructure parameters are applied based on their strategic importance. In this study, a depth of 1.80 m is used as the minimum operational threshold to assess whether a waterway can be considered potentially suitable for regular cargo transport under Baltic Sea region conditions. A depth of 1.80 m corresponds to the minimum transit depth for CEMT Class III according to Poland's inland waterway classification regulations (Rozporządzenie Rady Ministrów z dnia 7 maja 2002 r.) and aligns with the guaranteed draught for the E30 corridor downstream from Widuchowa to the Warta River mouth section [37] as follows:

$$I_2 = \frac{\text{Number of months per year with sufficient depth}(\geq 1.80 \text{ m})}{12}, \quad (2)$$

Sub-indicator I_2 measures the reliability of navigational depth, defined as the portion of the year during which a minimum depth of 1.8 m is maintained. Data on the navigation season and depths are provided in national statistics (Table 4).

Table 4. Depth parameters of inland waterways in the Baltic region.

Port	Operational Navigational Depth (m)	Navigation Season (Months)	Months with Depth of ≥ 1.8 m	Data Source
Klaipėda	1.8	8	8	AB Vidaus vandens kelių direkcija [76]
Gdańsk	2.5	10	9	Instytut Meteorologii i Gospodarki Wodnej, IMGW-PIB [77]
Gdynia	-	-	-	No IWT connection at the port, geographical constraint
Tallinn	-	-	-	No IWT connection at the port, geographical constraint
Riga	1.8	0	0	Latvijas vides, ģeoloģijas un meteoroloģijas centrs, Plūduriska information system [78]
HaminaKotka *	4.35	9.7	9–10	Saimaa Canal, Finland [79]
Szczecin	2.50	11.0	10–11	Regionalny Zarząd Gospodarki Wodnej w Szczecinie [80]

* The hinterland of the port of HaminaKotka is connected to the Saimaa Canal, which is a fully regulated canal with a lock system that ensures stable navigational depth. This significantly differs from natural rivers (such as Nemunas, Oder/Odra or Daugava), the navigational parameters of which depend on hydrological conditions and are subject to high variability. Source: Compiled by the authors based on the specified sources.

Table 4 combines different types of data (guaranteed, typical, and hydrologically variable depth parameters). To ensure comparability, a unified threshold criterion is additionally applied—the number of months per year during which the navigational depth is no less than 1.8 m. This approach allows for the evaluation of not only infrastructure parameters but also the actual operational accessibility of inland waterways.

The 1.8 m depth threshold is the only officially documented minimum operation draught standard identified for the Baltic region sample. It is established under Polish national inland waterway classification regulations and applied in practice as a reference minimum for E-class corridor compliance. For regulated canals such as the Saimaa Canal, navigational depth is structurally guaranteed by a lock system and treated accordingly in Table 4. A formal sensitivity test was not conducted. The directional ranking is not expected to change, as zero-group ports (Tallinn, Gdynia) have no navigable waterway regardless of the threshold.

Sub-indicator I_3 evaluates the accessibility of inland waterways, i.e., the period during which navigation is possible without seasonal restrictions. It is defined as the ratio of unrestricted navigation days to the total calendar days in a year, thereby integrating various seasonal and hydrological factors into a single normalised indicator.

Sub-indicator I_3 is calculated according to Formula (3):

$$I_3 = 1 - \frac{D_{restr}}{T}, \quad (3)$$

where D_{restr} is the duration of navigation restrictions, in days; T is the total number of days in a year.

In the model, the time period is approximated as 365 days, disregarding leap years, since variations in a single day do not significantly affect the results of transport systems and infrastructure evaluations. The number of navigation restrictions D_{restr} includes days when navigation is technically impossible or economically unviable due to the following:

- Ice cover, when navigation is seasonally suspended;
- Low water levels, when the depth falls below operational limits (e.g., approximately 1.50 m for lower-class waterways), allowing navigation only for vessels (barges) with very limited tonnage;
- High discharge (flooding), when the current speed exceeds safe navigation limits (often around 2 m/s in practice);
- Lock maintenance or repair work, when locks are temporarily closed.

Considering that inland waterways in the Baltic Sea basin are predominantly up to Class IV according to UNECE classification, the thresholds applied in this study reflect the operational conditions of these waterways (Table 5). The specified values are indicative, as precise limits depend on hydrological conditions, the waterway class, and the technical parameters of the vessels used. These thresholds are based on PIANC recommendations applied in international practice.

The value of sub-indicator I_3 approaches 1 when navigation restrictions are minimal and decreases as the duration of restrictions increases.

Seasonal restrictions are a multidimensional phenomenon, data of which are presented to varying degrees in national statistics. The 2 m/s current velocity threshold is used as an indicative operational restriction threshold rather than a universal legal standard [81]. Since international inland waterway guidance indicates that lower current velocities, around 1.5 m/s depending on vessel type and channel geometry, may already limit navigation, 2 m/s is treated here as a severe hydrological condition under which upstream cargo navigation may become restricted or economically impractical. Initial data suggest that the winter period (approximately December–March) is practically excluded from operational planning in the Baltic region, except for the port of Szczecin, which is located furthest south. In the Saimaa Canal, the situation is mitigated through the use of icebreakers. The primary risk factor is not ice but summer droughts (particularly in July–August), which can unexpectedly disrupt navigation.

Table 5. Restrictions on navigation conditions for inland waterways in the Baltic regions in 2023.

Port Hinterland	Ice Days (d/m.)	Low Water (d/m.)	Floods (d/m.)	Current > 2 m/s (d/m.)	Source
Klaipėda	30	70	0	0	Hydrological data of the Lithuanian Hydrometeorological Service [76]
Gdańsk	20	40	10	10	Instytut Meteorologii i Gospodarki Wodnej, IMGW-PIB [77]
Gdynia	-	-	-	-	Geographical constraint
Tallinn	-	-	-	-	Geographical constraint
Riga	-	-	-	-	Latvijas vides, ģeoloģijas un meteoroloģijas centrs, Pluduriska information system [78]
HaminaKotka	55	0	0	0	Saimaa Canal, Finland [79]
Szczecin	20	0	5	5	Regionalny Zarząd Gospodarki Wodnej w Szczecinie [80]

Source: Compiled by the authors based on the data provided in the specified sources.

Sub-indicator I_4 measures the level of integration of river information services (RIS), evaluating how widely digital navigation and traffic management solutions are integrated into physical inland waterway infrastructure. In this study, RIS coverage is interpreted through the typology of functionality levels (Table 6).

Table 6. Classification of maturity levels of river information services (RIS) and evaluation scale.

RIS Level	Description	Score
Level 0	No RIS	0
Level 1 (basic)	Static fairway information (navigation charts, depth maps)	25
Level 2 (intermediate)	Real-time information system (water level monitoring and basic vessel automatic identification system (AIS))	50
Level 3 (advanced)	Barge traffic management, lock automation, electronic reporting, incl. vessel traffic services (VTS), AIS, inland waterways Electronic Chart Display and Information System (ECDIS)	75
Level 4 (integrated)	Cross-border RIS integration, integration with Port Community Systems (PCS)	100

Source: Compiled by the authors according to [53,59,82].

The scale (Table 6) aligns with the implementation requirements of the directive and the digitalisation vision under NAIADES III. Data are collected based on information provided by national inland waterway administrations and port sources. The resulting sub-indicator value is normalised within the range [0; 1], where higher values indicate a higher level of digital navigation and vessel traffic management integration in IWT.

Sub-indicator I_5 measures the practical IWT handling capacity in port hinterlands. It is calculated as the ratio between terminal capacity and the actual flow of cargo transported via inland waterways (Formula (4)). This indicator is not interpreted as a measure of terminal efficiency or demand performance. Instead, it reflects the latent capacity, i.e., the margin between declared throughput capability and current utilisation. It indicates whether sufficient terminal infrastructure exists to support cargo transfer between inland waterway transport and other land transport modes. Adequate terminal capacity established ahead of demand is a prerequisite for corridor attractiveness, as terminal saturation may become

a bottleneck that suppresses IWT utilisation regardless of upstream waterway quality. In this sense, I_5 measures infrastructural positioning relative to current and potential demand, consistent with the supply-side focus of IWTI. Since I_5 uses actual cargo flow in the denominator, it is acknowledged as a hybrid supply-side indicator and is interpreted together with the remaining infrastructure-based sub-indicators rather than as a standalone measure of market demand.

$$I_5 = \frac{\sum_{i=1}^M C_{TER,i}}{F_{IWT}}, \quad (4)$$

where M is the number of intermodal terminals along inland waterways in the port hinterland; $C_{TER,i}$ is the design or actual annual capacity of the i -th terminal, in million tonnes; and F_{IWT} is the actual flow of cargo transported via inland waterways, in million tonnes.

Data about terminals operating in port hinterlands, their handling capacities, and cargo flows (Table 7) are collected from the Eurostat database (iww_go_atygo) and national statistical authorities (GUS, Statistics Finland, VVKD). For Lithuania and Finland, data on cargo flows are sourced from Eurostat, as the statistical accounting practice applied records inland waterways cargo flows based on the country of vessel registration (*flag-based reporting principle*). Therefore, Eurostat data ensure a consistent and comparable reflection of cargo flows, regardless of specific national accounting practices.

Table 7. Inland waterways terminal capacity and cargo flows in port hinterlands of the Baltic region in 2023.

Port	Inland Port Terminals	Terminal Capacity C_{TER} (t/m.)	IWT Cargo Flow F_{IWT} (t/m.)	Sources
Klaipėda	Ports of Kaunas and Jurbarkas	500,000	162,000	VVKD strategic plan (2022–2025) [83], cargo flow [84]
Gdańsk	Bydgoszcz terminal	2,000,000	414,000	Statistics Poland (GUS), Gdańsk [85,86]
Gdynia	-	-	-	Geographical situation
Tallinn	-	-	-	Geographical situation
Riga	-	-	-	No commercial navigation on the Daugava River
HaminaKotka	Saimaa system ports: Lappeenranta, Imatra, Joensuu, Varkaus, Kuopio	1,220,000	826,000	Statistics Finland [84,87]
Szczecin	Odra inland terminals	3,000,000	1,275,000	Statistics Poland, Szczecin [88]

Source: Compiled by the authors based on the specified sources.

For HaminaKotka, I_5 is calculated using 2022 cargo flow data, as commercial navigation on the Saimaa Canal was suspended in 2023 following the sanctions imposed after Russia's invasion of Ukraine. This represents a justified exception to the 2023 reference year and is noted in Table A3.

The sub-indicator is normalised on a $[0; 1]$ interval, which makes it possible to compare the practical trans-shipment infrastructure of different ports. I_5 assesses the infrastructure component in the supply chain and complements the inland waterway transport constraints described by I_2 (depth reliability) and I_3 (seasonal constraints).

The five IWTI sub-indicators cover different and mutually non-substitutable dimensions of infrastructural readiness, ranging from physical capacity and hydrological reliability to seasonal accessibility, digital infrastructure and the logistical capacity of terminals. Each sub-indicator is calculated using a separate formula, based on information from national statistical institutions and international inland waterways registers. The relative importance of the sub-indicators is determined by weights based on expert information, the determination procedure for which is described in the following section.

3.3. Expert Evaluation Procedure and Determination of Weights

The sub-indicator weights were determined using a direct normalisation method based on data from a structured expert survey ($n = 7$). Experts were selected based on two criteria: professional experience in IWT infrastructure, maritime logistics and transport planning, and direct familiarity with Baltic Sea region IWW networks. The aggregate profile of the expert panel is presented in Table 8.

Table 8. Aggregate profile of the expert panel.

Competence Area	Type of Institution	Professional Experience	Number of Experts
1. Inland waterway transport logistics and operation	Shipping/IWT operators	>10 years	3
2. Transport infrastructure planning and engineering	Research institutions	>8 years	2
3. Seaport management and hinterland logistics	Port and logistics companies	>12 years	2

Source: Compiled by authors.

The experts took part in the study voluntarily, which they declared verbally and anonymously; their personal information is not used in the study. According to Lithuanian national legislation regulating non-interventional professional research, the study did not require formal ethics approval.

The survey was conducted as a series of individual expert interviews over a three-month period. Each participant was presented with 14 inland waterways infrastructure parameters divided into three categories (technical, technological, navigational) and was asked to assess the importance of each parameter using a 5-point Likert scale (1—not important at all, 5—very important) and to assign a rank within each category.

The sub-indicator weights were derived in two stages as follows:

1. Thematically related parameters were assigned to each sub-indicator I_1 – I_5 (Table 8);
2. The weight base for each sub-indicator was calculated as the arithmetic mean of the average scores of the assigned parameters, and the resulting vector was normalised to a $[0; 1]$ scale ($\sum w_i = 1$).

The sub-indicator I_1 covers physical infrastructure parameters and reflects navigational capacity determined by the geometry of the fairway (static dimension). Sub-indicator I_2 is associated with hydrological conditions and shows depth reliability over time. It reflects hydrological reliability, the degree to which a waterway corridor provides consistent depth conditions for cargo transport. Sub-indicator I_3 describes the availability of navigation throughout the year by accounting for seasonal constraints (accessibility dimension). Sub-indicator I_4 indicates the level of development of digital management infrastructure, including the implementation and integration of RIS systems (technological dimension). Visibility/weather and traffic intensity parameters are assigned to I_4 on the basis that RIS systems, as defined in Directive 2005/44/EC, provide real-time information on these conditions as part of their core traffic and safety management functions extending beyond static nautical chart data. Sub-indicator I_5 reflects the capacity of inland waterway terminals relative to current cargo flows—the margin between declared throughput capabil-

ity and current utilisation. It is interpreted as a latent capacity reserve rather than a measure of operational efficiency (logistical dimension). A detailed allocation of parameters and the calculated weights are presented in Table 8.

Table 9 shows how the expert-rated technical, navigational and technological parameters were translated into the five IWTI sub-indicators. The highest weights assigned to I_1 and I_2 indicate that, in the experts' view, waterway class and depth reliability are the most critical prerequisites for IWT development. The lower weight of I_5 suggests that terminal capacity is important but becomes fully relevant only when basic navigability conditions are ensured. The indicator weights (Table 9) are calculated using the following standard normalisation expression:

$$w_i = \frac{\bar{x}_i}{\sum_{j=1}^5 \bar{x}_{agg}}, \quad (5)$$

where w_i is the weight of the i -th sub-indicator, and $\bar{x}_{agg}$ is the aggregated mean of the parameters associated with the sub-indicator, $j=1, \dots, 5$ denotes the five IWTI sub-indicators.

Table 9. Expert survey parameter-to-sub-indicator mapping and weight derivation.

IWTI Sub-Indicator	Expert Parameters	Parameter Group	Mean Rating $\bar{x}$	$\bar{x}_{agg}$	w_i
I_1 —Waterway CEMT class	Vessel dimensions	Technical	4.86	4.477	0.2497
	Bridge clearance	Technical	4.43		
	Fairway width	Technical	4.14		
I_2 —Depth reliability	River depth	Navigational	5.00	4.380	0.2443
	Water level fluctuations	Navigational	4.14		
	Lock size and location	Navigational	4.00		
I_3 —Seasonal accessibility	Ice conditions	Navigational	1.86	3.003	0.1675
	Currents and velocity	Navigational	3.86		
	Navigational obstacles	Navigational	3.29		
I_4 —RIS coverage	Navigation equipment	Technological	4.57	3.287	0.1833
	Visibility / weather	Navigational	3.00		
	Traffic intensity	Navigational	2.29		
I_5 —Terminal capacity	Cargo handling equipment	Technological	2.43	2.785	0.1553
	Infrastructure maintenance	Technical	3.14		
Σ				17.932	1.00

Note: $\bar{x}_{agg}$ = the arithmetic mean of the scores of the assigned parameters. Source: Compiled by the authors.

The base weights (Table 8) obtained through the expert survey are used in calculating the IWTI.

The five sub-indicator weights determined on the basis of the expert survey ($n = 7$) reflect the consensus of inland waterways infrastructure and logistics specialists regarding the relative importance of each dimension in the context of the eastern Baltic region. The resulting weights are directly incorporated into the TOPSIS calculation procedure as coefficients of the relative importance of each sub-indicator, which determine the formation of the final IWTI score according to each port's proximity to the ideal variant of infrastructural readiness.

3.4. TOPSIS Aggregation Method

IWTI is calculated using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. TOPSIS was chosen because it enables heterogeneous infrastructure sub-indicators to be aggregated into a single composite readiness score by measuring each port's relative distance from the positive ideal and negative ideal infrastructure profiles.

The method applies a compensatory aggregation logic, meaning that differences across sub-indicators affect the final score proportionally to their assigned weights. However, this compensability is interpreted only at the level of composite scoring and does not imply physical substitutability between infrastructure dimensions. For example, RIS coverage cannot compensate for the absence of navigable depth in operational terms. Therefore, the IWTI should be understood as a measure of composite infrastructural readiness rather than minimum-constraint feasibility. Compared with simple additive weighting, TOPSIS keeps both the positive and negative ideal reference points explicit. Compared with outranking methods such as ELECTRE, it does not require additional pairwise threshold parameters that would be difficult to justify empirically in a small regional sample. In addition, TOPSIS is widely used in transport and port studies, which makes it easier to compare the obtained results with other works [72,73].

The calculation is performed in several sequential steps. An initial data matrix is constructed containing the indicators for all ports under consideration. This matrix is then normalised so that all indicators become mutually comparable.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}}, \quad (6)$$

where x_{ij} is the value of sub-indicator j of the i -th port ($n = 7$).

The normalised values are multiplied by the expert weights w_j , yielding a weighted normalised matrix:

$$v_{ij} = w_j \times r_{ij}, \quad (7)$$

The positive ideal solution A^+ and the negative ideal solution A^- are then determined:

$$A^+ = \{ \max(v_{ij}) \}, \quad A^- = \{ \min(v_{ij}) \}, \quad (8)$$

The distances of each port from the ideal solutions are calculated using the Euclidean metric (D_i^+ , D_i^-).

$$D_i^+ = \sqrt{\sum_j (v_{ij} - v_j^+)^2}, \quad D_i^- = \sqrt{\sum_j (v_{ij} - v_j^-)^2}, \quad (9)$$

The final IWTI score for each port i is calculated as follows:

$$IWTI_i = \frac{D_i^-}{D_i^+ + D_i^-} \in [0; 1], \quad (10)$$

The index approaches 1 when the port is closest to the positive ideal and approaches 0 when it is closest to the negative ideal. The calculations were carried out in the Microsoft Excel environment.

The TOPSIS method aggregates the five structurally different sub-indicators into a single IWTI score by assessing each port's relative distance from the positive ideal and negative ideal infrastructure profiles. This provides a transparent and replicable ranking procedure after normalisation and expert weighting. The resulting score should be interpreted as a measure of composite infrastructural readiness, not as proof that all operational constraints are removed. In cases where all sub-indicators are zero, no cross-dimensional compensation is possible, and the port remains in the zero-readiness group. For active corridor ports, TOPSIS allows differences in technical, operational, digital and terminal-related conditions to be reflected in the final ranking while keeping the ideal reference points explicit.

3.5. Sensitivity Analysis

The final IWTI score depends on the choice of expert weights; therefore, a sensitivity analysis is carried out to ensure the reliability of the methodology and the stability of the results. This is done by testing three alternative weighting scenarios and assessing the consistency of the rankings using Spearman's rank correlation coefficient. Each scenario represents a different methodological position on the relative importance of the sub-indicators (Table 10):

- Scenario 1 uses weights based on data from the expert survey. This scenario is considered the baseline, as the weights reflect empirically grounded expert views on the importance of each inland waterway's transport infrastructure dimension for a Baltic Sea region port.
- In Scenario 2, all five sub-indicators are assigned an equal weight ($w = 0.20$). This scenario tests the hypothesis of whether the ranking of weights remains stable when any prioritisation is removed. The equal-weights scenario is standard practice in the calculation of composite indices [71].
- Scenario 3 gives preference to technical dimensions over the other sub-indicators. Sub-indicators I_1 and I_2 are doubled in proportion to their baseline values, and the weights of the remaining sub-indicators are proportionally reduced (Table 10).

Table 10. Weight scenarios for sensitivity analysis.

Sub-Indicator	W1	W2	W3
I_1 —Waterway CEMT class	0.2497	0.20	0.3816
I_2 —Depth reliability	0.2443	0.20	0.3733
I_3 —Seasonal accessibility	0.1675	0.20	0.0640
I_4 —RIS coverage	0.1833	0.20	0.0980
I_5 —Terminal capacity	0.1553	0.20	0.0831

Table 10 presents the three weighting schemes used to test the sensitivity of the IWTI ranking. The scenarios compare the expert-based baseline weights (W1) with equal weighting (W2) and a technically oriented weighting structure (W3), thereby showing whether the final ranking depends strongly on the selected weight assumptions.

An additional infrastructure potential scenario analysis (W4) was carried out by modelling the impact of the implementation of documented investments on IWTI. The scenario is an infrastructure potential sensitivity test rather than a predictive forecast. The modelled interventions differ by their official status and are detailed below:

1. Gdynia—connection via the Martwa Wisła (CEMT Class II) to the E40/E70 corridor, enabling access to the Bydgoszcz terminal ("Sustainable Transport Development Strategy until 2030", Council of Ministers resolution on the long-term programme "Development of the Lower Vistula" (2023) [89]. Modified sub-indicators: I_1 , I_3 , I_4 , and I_5 .
2. Riga—lock construction on the Daugava River, based on the approved but unimplemented EMMA Project Consortium (2020) plan. No terminal infrastructure expansion is assumed. Modified sub-indicators: I_1 , I_2 , and I_3 .
3. HaminaKotka—partial recovery of Saimaa Canal commercial traffic to approximately 50% of the 2019 level (~490,000 tonnes in international traffic), contingent on geopolitical conditions. Modified sub-indicator: I_5 .
4. Gdańsk, Tallinn, Klaipėda—no change.

In all cases, only those sub-indicators are modified for which official documentation or clearly defined assumptions exist.

Three ports whose hinterlands have identified investment projects under implementation are included in the W4 scenario. In the hinterland of the Port of Gdynia, a connection via the Martwa Wisła (Class II) to E40/E70 is planned, with the intention of using the capacity of the Bydgoszcz terminal. The Port of Riga remains conservative. Although projects for the construction of locks (EMMA project) have been approved, no further expansion of terminal infrastructure is planned. At HaminaKotka, intensive cargo navigation on the Saimaa Canal has not taken place since 2022 due to the war with Russia. However, if the flow were to recover to about 50% of the 2019 level, potential changes should be reflected in the development of the port's inland waterway transport potential. Gdańsk and Tallinn are left unchanged—the former as an operational infrastructure without new investments, the latter due to the absence of an inland waterways connection.

The stability of rankings between scenarios is assessed using Spearman's rank correlation coefficient.

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)}, \quad (11)$$

where d_i is the rank difference in a port between two scenarios; $n = 7$ —the number of alternatives. The coefficient value $\rho > 0.90$ indicates high rank stability, while $\rho < 0.80$ would indicate that the final ranking is significantly sensitive to the choice of weights.

The IWTI construction methodology described in this section consists of four inter-related stages: formation of the research sample, construction of sub-indicators, determination of expert weights and TOPSIS aggregation. The seven selected ports in the Baltic Sea region form an analytically homogeneous sample, enabling comparison of different types of infrastructural cases. The five sub-indicators capture different dimensions of infrastructural readiness; their weights are based on empirical expert assessments, and TOPSIS aggregation ensures a methodologically sound construction of the final index. This structure makes it possible not only to compare the inland waterway transport potential of port hinterlands on the basis of existing infrastructure but also to model possible changes, which are discussed in the sensitivity analysis and the infrastructure potential scenarios.

4. Results

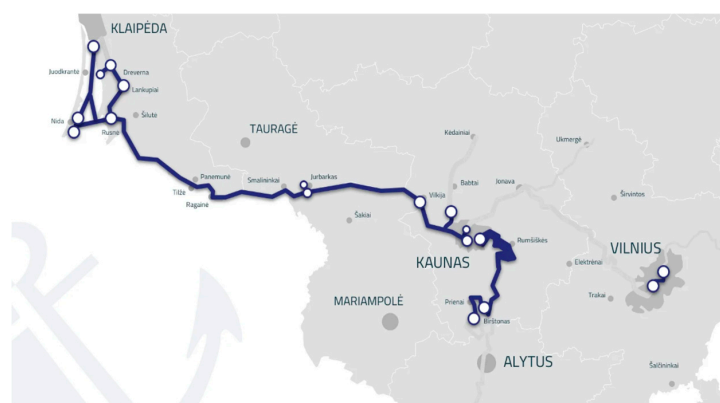
4.1. Sub-Indicator Values Received

The values of the five sub-indicators of the composite IWTI were calculated for all seven Baltic Sea ports using the methodology described in Section 3.

The operational status and CEMT classes of the corridors shown in the map panels (Figure 2) are described in the accompanying text and summarised in Table 11. In Lithuania, the E41 inland waterway navigation corridor from Kaunas to the Port of Klaipėda is operational (Figure 2a). Its characteristics differ by section: from Jurbarkas to the Port of Klaipėda is classified as Class IV (165 km), while the “Jurbarkas–Kaunas” section is classified as Class III (126 km).

In Poland, the E30 (Odra/Oder), E40 and E70 (Vistula) corridors are in operation. The E30 corridor runs along the Odra/Oder River from the Port of Szczecin southwards. The lower Odra/Oder (estuarine and downstream section) is Class III–IV (Figure 2c). The E40 and E70 corridors run along the Vistula River from the Port of Gdańsk southwards to Toruń (Class II–III). The section consists of two segments: the Gdańsk–Tczew segment (Class III, ~31 km) and the Tczew–Bydgoszcz segment (Class II, ~139 km).

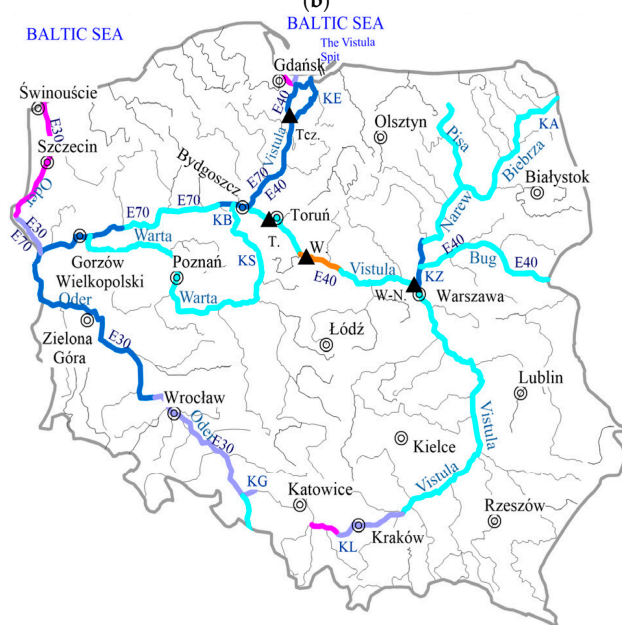
The E70 continues westwards along the Noteć River, the Bydgoszcz Canal and the Brda River, linking Gdańsk with the western regions of Poland and Germany (Class III) (Figure 2c). The Szczecin–Kostrzyn segment is about 120 km long and has Class III characteristics. In the lower part of the Odra/Oder, the Kostrzyn–Wrocław segment is canalised, about 200 km long and meets Class IV requirements.



(a)

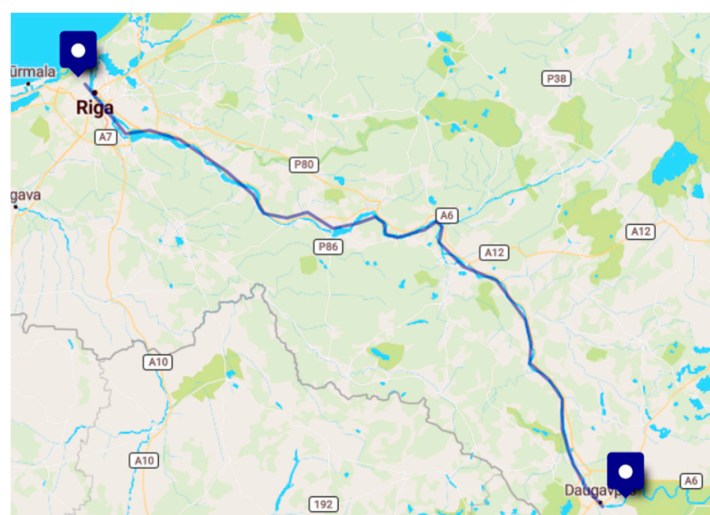


(b)



(c)

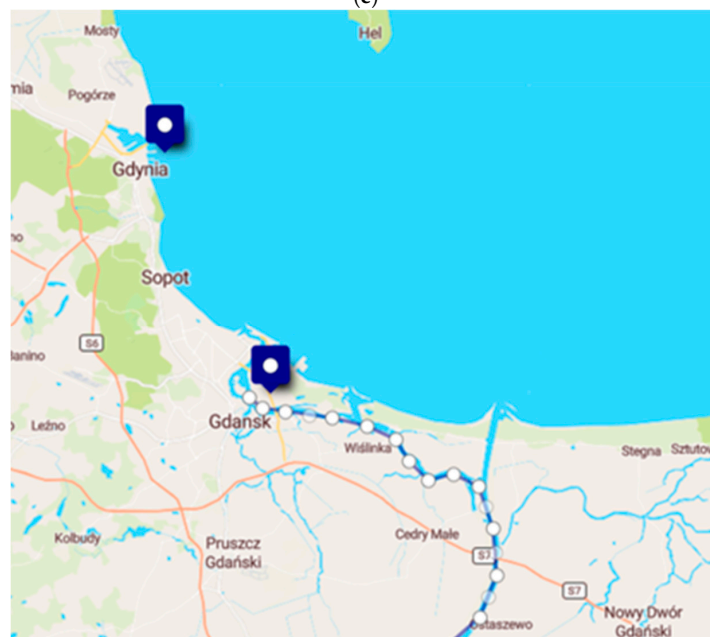
Figure 2. Cont.



(d)



(e)



(f)

Figure 2. Inland waterway corridors of the analysed Baltic Sea port hinterlands: (a) E41—Nemunas, Lithuania; (b) Saimaa Canal system, Finland; (c) E30, E40, E70—Oder/Odra and Vistula, Poland; (d) Daugava—infrastructural barrier, Latvia; (e) Tallinn, Estonia, no IWT connection; (f) E40/E70—lower Vysla, Gdańsk–Gdynia area, Poland. Source [6,89].

Table 11. Weighted average CEMT class of segments and final I_1 value.

Port	AGN Corridor	CEMT Class of Segment 1	Length of Segment 1, km	CEMT Class of Segment 2	Length of Segment 2, km	Calculated I_1
Klaipėda	E41	4.00	165	3.00	126	3.57
Gdańsk	E40, E70	3.00	31	2.00	139	2.18
Gdynia	-	0	0	0	0	0
Riga	AGN potential	0	0	0	0	0
Tallinn	-	0	0	0	0	0
HaminaKotka	Saimaa (FI)	4.00	857			4.00
Szczecin	E30	3.00	120	4.00	200	3.63

Source: Compiled by the authors according to [37,38,75].

The Port of Gdynia has no direct inland waterway connection, although it is located close to Gdańsk. A potential connection via the Martwa Wisła to E40/E70 is considered in the W4 scenario (Figure 2f).

The Saimaa Canal connects the Port of HaminaKotka with the Saimaa lake system in the interior of Finland. The canal is 42.9 km long, has eight locks, a guaranteed draught of 4.35 m and an extended navigation period through the use of icebreakers (Figure 2b). This waterway is classified as Class IV. Part of the canal runs through Russian territory, which is an important geopolitical aspect that led to the suspension of commercial traffic from 2022. Any resumption of cargo flows after the end of the war will be included in the W4 scenario.

The Daugava River flows through Riga into the Baltic Sea (Figure 2d). Although the river has AGN-classified potential (Class III–IV), three hydroelectric dams (Kegums, Pļaviņas, Riga) were built without locks, which completely block navigation upstream and prevent any actual commercial navigation.

There are no inland waterway corridors in Estonia, and Tallinn has no connection to any river system. This case was selected as a control case in the study.

Based on the collected information, a table for the CEMT class sub-indicator I_1 was compiled, with a final indicator for each port calculated using Formula (1) (Table 11).

Table 11 indicates the structural technical capacity of each inland waterway corridor. Higher I_1 values reflect corridors with higher CEMT classes and longer higher-class segments, while zero values indicate the absence of a functional inland waterway connection to the port hinterland.

It was found that the Gdańsk water corridor has the lowest category (2.18), which means that it can be navigated by local vessels of up to 650 tonnes capacity and with a draught not exceeding 1.8 m.

The depth reliability sub-indicator I_2 was calculated using the data presented in Table 4 and Formula (2). The waterway seasonality sub-indicator I_3 was calculated using Formula (3) and the data in Table 5. The inland waterways cargo handling terminals sub-indicator I_5 was calculated using Formula (4) and the data in Table 7. The calculation of these sub-indicators is presented in Appendix A, Tables A1–A3.

The level of integration of river information systems is assessed by analysing the information provided by the countries (Table 12).

Table 12 shows clear differences in the level of digital navigation and traffic management infrastructure across the analysed corridors. Higher I_4 values indicate the presence of advanced RIS functions such as AIS, Notices to Skippers (NtS), vessel traffic services (VTS) and lock automation, while lower values reflect limited or absent digital support for IWT operations.

Table 12. Determination of RIS coverage and final I_4 value.

Port	RIS Level	RIS System Description	Verification Source	Calculated I_4
Klaipėda	2	Wave app, Notices to Skippers (NtS); interactive navigational charts (Inland ECDIS)	VVKD [76]	0.5
Gdańsk	1	Basic digital navigational charts only	[89]	0.25
Gdynia	0	RIS not applied	-	0
Riga	0	RIS not applied	-	0
Tallinn	0	RIS not applied	-	0
HaminaKotka	3	Full Saimaa vessel traffic system (VTS): (VTS + AIS + NtS + lock automation)		0.75
Szczecin	3	Full RIS on the lower Odra—VTS, AIS, NtS, Inland ECDIS	[48,49,89,90]	0.75

Note: RIS levels follow the typology defined in Table 6. I_4 = RIS level score/100. Source: Compiled by the authors according to the specified sources.

Values of the sub-indicator I_4 reveal a large difference between the ports analysed. HaminaKotka and Szczecin achieve the highest score (0.75)—their corridors have full RIS systems with lock automation and vessel tracking. The inland waterway transport hinterland of the Port of Klaipėda (0.50) has functioning digital navigation infrastructure, but cross-border integration has not yet been implemented. Gdańsk (0.25) has only static electronic navigational charts, and Gdynia, Riga and Tallinn receive no score, as they have no inland waterways connection.

Having completed all the calculations, Table 13 of the IWTI sub-indicators is compiled.

Table 13. IWTI sub-indicator values by port hinterland.

Port	I_1 —CEMT	I_2 —Depth Reliability	I_3 —Seasonal Accessibility	I_4 —RIS Coverage	I_5 —Terminal Capacity
Klaipėda	3.567	0.667	0.726	0.50	3.086
Gdańsk	2.182	0.750	0.781	0.25	4.831
Gdynia	0	0	0	0	0
Riga	0	0	0	0	0
Tallinn	0	0	0	0	0
HaminaKotka	4.00	0.808	0.849	0.75	1.477
Szczecin	3.625	0.875	0.918	0.75	2.353

Source: Compiled by the authors.

Table 13 presents three structurally different port profiles. The first group consists of ports with an active inland waterways corridor—Szczecin, HaminaKotka and Klaipėda—whose values are positive in all five dimensions. The HaminaKotka hinterland has the best inland waterways class (4.00), but due to a shorter navigation period, depth reliability and seasonal accessibility are lower than in the waterways of the Szczecin hinterland.

4.2. Final IWTI Scores and Ranking of IWT Potential in Port Hinterlands

Using the methodology described in Sections 3.2 and 3.3, the sub-indicator data presented in Table 12 were processed using the TOPSIS procedure (Formulas (6)–(10)). In the first step, the sub-indicator values for each port were normalised using the vector method (Formula (6)) (Table 14), and the resulting matrix was multiplied by the expert weights (Table 9) calculated according to Formula (5) (Table 15). After determining the positive (A^+) and negative (A^-) ideal solutions, the Euclidean distances D^+ and D^- were

calculated for each port (Formula (9)). The final IWTI score for each port was obtained using Formula (10) and is presented in Table 16 together with the intermediate D^+ and D^- values, which make it possible to assess each port's relative distance from the best and worst infrastructural variants.

Table 14. Normalised IWTI matrix.

Port	$r(I_1)$	$r(I_2)$	$r(I_3)$	$r(I_4)$	$r(I_5)$
Klaipėda	0.5224	0.4280	0.4481	0.4170	0.4845
Gdańsk	0.3196	0.4815	0.4751	0.2085	0.7853
Gdynia, Riga, Tallinn	0	0	0	0	0
HaminaKotka	0.5858	0.5190	0.5168	0.6255	0.2319
Szczecin	0.5309	0.5618	0.5585	0.6255	0.3694

Source: Compiled by the authors.

Table 15. Weighted normalised IWTI matrix.

Port	$v(I_1)$	$v(I_2)$	$v(I_3)$	$v(I_4)$	$v(I_5)$
Klaipėda	0.1304	0.1046	0.0740	0.0764	0.0752
Gdańsk	0.0798	0.1176	0.0796	0.0382	0.1178
Gdynia, Riga, Tallinn	0	0	0	0	0
HaminaKotka	0.1463	0.1268	0.0866	0.1147	0.0360
Szczecin	0.1326	0.1372	0.0936	0.1147	0.0574
A^+	0.1463	0.1372	0.0936	0.1147	0.1178
A^-	0	0	0	0	0

Source: Compiled by the authors.

Table 16. Final IWTI scores and ranking.

Port	D^+	D^-	IWTI	Ranking
Szczecin	0.0619	0.2482	0.800	1
Klaipėda	0.0705	0.2120	0.750	2
HaminaKotka	0.0827	0.2437	0.747	3
Gdańsk	0.1041	0.2046	0.663	4
Riga, Gdynia, Tallinn	0.2757	0	0	5–7 *

* Note: Riga, Gdynia and Tallinn obtain identical IWTI = 0.000 values, as all their sub-indicator values are equal to zero. Their zero values reflect distinct conditions: geographical absence of any IWT system (Tallinn), missing link infrastructure to an adjacent corridor (Gdynia), and blocked corridor potential due to hydroelectric dams (Riga). The mutual ranking of these three ports is analytically insignificant—they constitute a single bottom group representing zero infrastructural readiness for inland waterway transport. Source: Compiled by the authors.

A final IWTI table by port hinterland is then compiled, and the ranking of hinterland infrastructure potential is determined (Table 16):

According to the IWTI values, the Szczecin hinterland has the highest inland waterway transport infrastructure potential, with a score of 0.800 (Table 16). Klaipėda and HaminaKotka form a group with similar results, occupying second and third place respectively, while the Gdańsk hinterland shows medium infrastructural readiness. Riga, Gdynia and Tallinn, according to the applied sub-indicators, do not exhibit significant inland waterway transport infrastructure potential; therefore, their mutual ranking should be regarded as merely formal rather than analytically meaningful. These results are used in the sensitivity analysis.

4.3. Sensitivity Analysis Results

The sensitivity analysis is carried out for three scenarios: the baseline (W1), equal weights for all sub-indicators (W2), and a scenario where technical sub-indicators are given

priority (W3) (Table 10). In each scenario, the TOPSIS procedure is repeated with the corresponding weight vectors, new IWTI scores and port rankings are obtained, and rank stability between scenarios is assessed using Spearman's correlation coefficient (Formula (11)). Table 17 presents the results.

Table 17. Results of the IWTI sensitivity analysis.

Port	W1 IWTI	W1 Rg	W2 IWTI	W2 Rg	W3 IWTI	W3 Rg	Ranking Δ
Szczecin	0.8003	1	0.7532	1	0.8868	1	=
Klaipėda	0.7504	2	0.7240	2	0.8050	3	▼1
HaminaKotka	0.7466	3	0.6848	3	0.8672	2	▲2
Gdańsk	0.6628	4	0.6812	4	0.6685	4	=
Gdynia, Riga, Tallinn	0.0000	5–7	0.0000	5–7	0.0000	5–7	
$\rho(W1, W2)$ *		1.00					
$\rho(W2, W3)$ *					0.9643		
$\rho(W1, W3)$ *				0.9643			

Note: * Spearman's rank correlation coefficients.

The sensitivity analysis confirms a high degree of stability in the IWTI ranking. The Spearman's correlation coefficient between the baseline and equal-weights scenarios is $\rho(W1, W2) = 1.000$, and $\rho(W1, W3) = 0.964$ between the baseline and technical weights, which means that the ranking remains practically unchanged regardless of the choice of weights.

The only noticeable change is observed between Klaipėda and HaminaKotka: in the W3 scenario, HaminaKotka moves up to second place (Table 17), while Klaipėda drops to third. This change is explained by the fact that when the weights of the technical sub-indicators are doubled, HaminaKotka's advantage due to the highest I_1 value (4.00—Saimaa Canal, Class IV along the entire 857 km corridor) becomes decisive. The IWTI = 0.000 values of the three ports in the bottom group (Riga, Gdynia, Tallinn) remain unchanged in all scenarios—this confirms that zero sub-indicator values constitute an absolute infrastructural constraint that is insensitive to weight variations.

4.4. Scenarios for the IWT Infrastructure Potential

The study also includes an inland waterway transport infrastructure potential scenario analysis (W4), which models the impact of documented investments or geopolitical changes on IWTI. The scenario is based on a conservative principle—only those sub-indicators are changed for which official investment plans or documented political decisions exist. Four ports—Klaipėda, Gdańsk, Szczecin and Tallinn—remain unchanged in the W4 scenario: the first three because of their high baseline level of infrastructural readiness, and Tallinn because of an absolute geographical constraint.

For Gdynia, a connection via the Martwa Wisła (CEMT Class II, ~35 km) to the E40/E70 corridor is modelled, providing access to the capacity of the Bydgoszcz terminals. This solution effectively allows Gdynia to appropriate the infrastructural potential of the Gdańsk corridor: I_1 rises from 0 to 2.00, I_3 to 0.81, I_4 to 0.25 (basic RIS level), and I_5 to 4.83, which corresponds to the inland waterway transport network parameters of the Gdańsk hinterland, since both ports would be using the same system.

The Riga case is modelled conservatively because although lock construction at the Daugava hydropower plants is being planned [6], it has not yet been implemented. Therefore, I_1 is changed to 1.50 (partial navigation infrastructure) and I_3 to 0.30, reflecting limited seasonal accessibility without the full operation of a lock system. I_4 remains 0, as there is no RIS infrastructure, and $I_5 = 0$ because an inland terminal network in the Daugava basin

does not exist and is not planned. I_2 is set at 0.50, reflecting the hydrological potential of the Daugava under partial infrastructure.

For HaminaKotka, the resumption of commercial traffic on the Saimaa Canal to approximately 50% of the pre-sanctions (2019) level is modelled as a conservative sensitivity scenario, based on the unchanged technical parameters and structural continuity of the canal infrastructure. Before the 2022 sanctions, the canal and the connected inland waterway system handled ~1.7 million tonnes of cargo annually, including around 980K tonnes in international traffic and 708K tonnes in domestic traffic [89]. In 2023 and 2024, international cargo flows were suspended due to the sanctions imposed after Russia’s invasion of Ukraine. Therefore, the current interruption reflects geopolitical constraints rather than a loss of infrastructure capacity. All physical and digital sub-indicators (I_1 – I_4) remain unchanged, while I_5 increases from 1.48 to 3.00, reflecting higher utilisation of terminal capacity once flows are restored.

The W4 scenario reveals significant IWTI changes in three ports (Table 18). HaminaKotka moves up to first place (+0.1120, ▲2), as the resumption of commercial traffic unlocks latent potential that the existing physical infrastructure can realise without additional investment. Gdynia shows the largest absolute jump (+0.448, ▲1)—the connection to E40/E70 via the Martwa Wisła transforms its position from the zero group to fifth place. Riga’s increase (+0.349) is smaller than that of Gdynia, despite its higher AGN potential. The value $I_5 = 0$ reflects the absence of terminal infrastructure even in the lock-construction scenario.

Table 18. Changes in IWTI having implemented infrastructure potential scenarios.

Port	IWTI W1 (Basic)	Ranking W1	IWTI W4 (Potential)	Ranking W4	Δ IWTI	Δ Rank
Szczecin	0.8003	1	0.8293	2	+0.029	▼1
HaminaKotka	0.7466	3	0.8665	1	+0.112	▲2
Klaipėda	0.7504	2	0.7596	3	+0.009	▼1
Gdańsk	0.6628	4	0.6548	4	−0.008	=
Gdynia	0.0	5–7	0.4484	5	+0.448	▲1
Riga	0.0	5–7	0.3488	6	+0.349	▲1
Tallinn	0.0	5–7	0.0	7	0.00	=
$\rho(W1, W4)$			0.857			

Source: Compiled by the authors.

Klaipėda and Szczecin experience a relative decline in rank (▼1) due to the effect of TOPSIS normalisation rather than any deterioration in infrastructure. Tallinn remains unchanged (IWTI = 0.000); the geographical constraint is absolute. Spearman’s correlation $\rho(W1, W4) = 0.857$ confirms sufficient overall ranking stability despite individual changes.

5. Discussion

The IWTI makes it possible to systematically assess and compare the infrastructural readiness of inland waterway transport in a region where the waterway potential in port hinterlands remains structurally underused despite favourable geographical conditions. The results show that the inland waterway transport potential in the eastern Baltic region is structurally differentiated and cannot be treated as homogeneous—differences in infrastructural readiness between ports are significant and can be clearly distinguished methodologically. For example, the inland waterway network infrastructure potential in the Gdańsk hinterland (IWTI_{Gdańsk} = 0.6628) is 17% lower than in the Szczecin hinterland (IWTI_{Szczecin} = 0.8003). The chosen supply-side assessment approach, measuring infrastructural capacity rather than actual flows, proved methodologically appropriate for this

type of study. Actual inland waterway flows in the Baltic region are too low to differentiate ports according to their structural potential, so an index constructed purely on flows would assign almost identical values to all ports and would have no discriminating power.

Compared with SITCIN, IWTI provides greater discriminatory capacity at the level of port inland waterway networks, which is particularly relevant in regions where national statistics are uniformly low and do not differentiate structurally distinct hinterland corridors [66,67].

The IWTI showed that in the Baltic Sea region in 2023, the leading position was held by the Port of Szczecin (IWTI = 0.800). This reflects the composite advantages of the lower Odra hinterland corridor—the longest navigation season in the region ($I_3 = 0.918$), functioning RIS infrastructure ($I_4 = 0.75$) and the highest terminal capacity in relation to actual flows ($I_5 = 2.3529$). This result is consistent with findings in the literature in which the Odra corridor is identified as one of the most promising candidates for inland waterway transport integration in the Central European context [89,90].

Klaipėda's second place (IWTI = 0.750) reveals the structural potential of the Nemunas hinterland corridor, which is constrained by seasonal hydrological factors—summer drought periods that are an increasing consequence of climate change in the Baltic region [25,28].

HaminaKotka's third position (IWTI = 0.747) should be interpreted with caution: the baseline score is suppressed by the geopolitically constrained I_5 value, while the W4 scenario shows that the resumption of commercial traffic on the Saimaa Canal would transform this port into a regional leader. This supports the conclusion that the waterway potential of the HaminaKotka hinterland is latent rather than structurally limited.

The zero baseline scores of Riga and Gdynia confirm earlier findings regarding the importance of infrastructural barriers to inland waterway transport development in port hinterlands [3,45,89,91]. The W4 scenario results make it possible to identify three distinct types of investment priorities in hinterland waterway infrastructure: connection infrastructure (Gdynia, +0.448), complex hydrotechnical and logistics investments (Riga, +0.349) and geopolitically driven flow restoration (HaminaKotka, +0.120). Each requires different policy measures and funding mechanisms. The results show that the potential growth of the Riga hinterland is lower than that of Gdynia despite the more favourable characteristics of the Daugava River. The absence of inland ports ($I_5 = 0$) reflects the fact that lock construction in the Daugava hinterland corridor, without parallel development of terminal infrastructure, creates only partial potential. This finding confirms the complementarity principle between the physical, navigational, and logistical infrastructure identified in the literature [19,45,92]. I_5 must therefore be interpreted together with the physical and navigational sub-indicators. Where functional IWT terminal infrastructure is absent, $I_5 = 0$ indicates the absence of an operational handling base rather than unused reserve capacity. Where terminal infrastructure exists, but current flows are low, I_5 reflects latent terminal capacity relative to current utilisation. This distinction becomes visible in the W4 scenario, where connection infrastructure, terminal availability and geopolitical flow restoration affect the final IWTI score differently.

The sensitivity analysis ($\rho \geq 0.964$) confirms the internal rank stability and the methodological robustness of IWTI with respect to the choice of weights. This is in line with recommendations in the composite indices literature on managing weight uncertainty [66,68]. It should be noted, however, that internal rank stability must not be conflated with external validation. Validation against observed modal shares or corridor throughput data was not conducted in this study but remains a direction for future research. The only ranking fluctuation between Klaipėda and HaminaKotka was in the W3 scenario. This reflects a genuine methodological trade-off: the technical infrastructure dimension (I_1 , I_2) and

the operational dimension (I_5) can generate different priorities depending on the policy context. Sensitivity analysis thus provides decision-makers with a flexible instrument for quantifying the impact of alternative weighting assumptions on the final ranking.

Ports with a complete absence of infrastructure across all dimensions (Gdynia, Riga, Tallinn) receive $IWTI = 0$ regardless of the weighting scheme, because TOPSIS cannot generate compensation when all sub-indicators are simultaneously zero. For active corridor ports, the compensatory logic operates only at the level of composite scoring. It does not imply that digital infrastructure can physically replace navigable depth or remove hydrological constraints. Instead, it allows each port hinterland's overall infrastructure profile to be compared against the positive and negative ideal reference points. Empirically, its effect is minor, as confirmed by the sensitivity analysis ($\rho \geq 0.964$ across all weighting scenarios).

Since the adoption of the RIS Directive (2005/44/EC), digital navigation management infrastructure in Europe has expanded significantly. The EU-funded RIS COMEX project, which brought together 14 inland waterway administrations from 13 countries, delivered two key results: the EuRIS platform, which integrates all RIS information and services into a single European information environment, and CEERIS, which introduced an electronic reporting system in the Danube basin covering vessel, voyage and cargo information [55]. The COMEX² consortium ensures the continuity of these initiatives. The development of these platforms in the Baltic region will directly affect the values of sub-indicator I_4 . At present, the low value for Gdańsk (0.25) and the medium value for Klaipėda (0.50) on the RIS coverage sub-indicator are among the structural factors that could increase IWTI scores without additional investment in physical infrastructure. The NAIADES III action programme identifies the evolution of the RIS network at the EU level as one of the main directions for the inland waterway transport modernisation up to 2030 [59], and the TEN-T network revision (2021–2027), which has included additional inland waterways in the core and comprehensive network corridors, creates an institutional basis for investments that IWTI can help to prioritise using an objective quantitative method. This is particularly important for ports where hinterland waterway potential remains underused due to structural rather than geographical reasons.

The study has also identified its limitations and directions for future research. The expert survey ($n = 7$) used for weight determination should be viewed as a pilot study that produced methodologically sound and internally consistent results, but the sample size limits the possibility of generalising the weight structure at a broader regional level. A planned continuation of the research foresees an expanded expert survey that would include more experts from all the countries analysed and additional inland waterways specialists. This would make it possible to verify whether the weights identified in this study reflect a broader expert consensus or are sensitive to the geographical composition of the expert group. Future applications of the IWTI should include external validation against observed inland waterway modal shares, corridor throughput, or port-level hinterland flow data. This would help assess the index's generalizability beyond the analysed Baltic regional port sample.

The supply-side assessment approach that proved effective in this study can also be applied to analyse hinterland waterway potential in other European regions. For example, in the Danube basin and along the Baltic–Adriatic corridor, actual inland waterway flows similarly do not reflect the real infrastructural potential.

Beyond freight logistics, the IWTI can also be used as a starting point for discussing the wider role of inland waterways in regional development. Inland waterway corridors may improve access to rural areas and support the revitalisation of inland riparian regions. However, these effects are not measured directly in this study. Their assessment would

require additional socioeconomic indicators and is, therefore, proposed as a direction for future interdisciplinary research.

The plan is to extend the study in two directions. First, to carry out time-series analysis of inland waterway transport in selected port hinterlands, as multi-year information would make it possible to observe the dynamics of infrastructural readiness and to assess the impact of specific investments. The second direction is to integrate IWTI into broader port competitiveness models, which would provide a more comprehensive picture of the conditions for realising inland waterway transport potential. The structural differentiation between port hinterland inland waterway corridors identified in this study provides an empirical basis for further modelling and for formulating policy recommendations in the field of inland waterway transport development in the Baltic region.

6. Conclusions

This study developed a composite inland waterway transport infrastructure index (IWTI) designed to assess infrastructural readiness for inland waterway transport development in the hinterlands of regional seaports. The index integrates five dimensions—technical capacity, depth reliability, seasonal accessibility, RIS coverage and terminal capacity—and is calculated using the TOPSIS method with expert-determined weights.

The empirical results show significant differentiation of infrastructural potential in the eastern Baltic Sea region. Szczecin displays the highest level of readiness, while Klaipėda and HaminaKotka demonstrate high, but differently constrained, potential. Gdynia, Riga and Tallinn are identified as structurally constrained cases due to the absence or insufficient development of inland waterway transport infrastructure.

The sensitivity analysis confirmed a high degree of index stability ($\rho \geq 0.964$), while the scenario analysis showed that infrastructural interventions can fundamentally alter port positions, particularly in the cases of Gdynia and HaminaKotka. The results also confirm the importance of complementarity between physical and logistics infrastructure in shaping inland waterway transport potential.

From a methodological perspective, the study proposes a new, replicable index focused on supply-side infrastructural assessment and demonstrates the suitability of TOPSIS for integrating heterogeneous transport indicators. Direct application to other regional contexts would require recalibration. Sub-indicator thresholds and expert weights reflect Baltic Sea region conditions and should not be transferred without an independent regional expert survey. At a practical level, IWTI can be applied to identify investment priorities and plan port hinterland transport systems in the context of TEN-T and NAIADDES III.

The limitations of the study relate to the small expert sample and the use of single-year information. Future research should expand the expert evaluation, apply time-series analysis, external validation, and integrate IWTI into broader models of port competitiveness.

Author Contributions: Conceptualisation, V.L. and K.Č.; methodology, V.L. and K.Č.; software, V.L.; validation, V.L. and K.Č.; formal analysis, V.L. and K.Č.; investigation, V.L. and K.Č.; resources, V.L. and K.Č.; data curation, V.L. and K.Č.; writing—original draft preparation, V.L. and K.Č.; writing—review and editing, V.L. and K.Č.; visualisation, V.L. and K.Č.; supervision, K.Č.; project administration, K.Č.; funding acquisition, K.Č. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are available after request to the corresponding author.

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

Appendix A

Table A1. Calculation of I_2 based on the data of 2023.

Port	Operational Navigation Depth (m)	Navigation Season (Months)	Months with Depth ≥ 1.8 m	I_2
Klaipėda	1.8	8	8	0.667
Gdańsk	2.5	10	9	0.750
Gdynia	-	-	-	0
Tallinn	-	-	-	0
Riga	1.8	0	0	0
Szczecin	2.50	10.5	10–11	0.875
HaminaKotka	4.35	9.7	10	0.808

Table A2. Calculation of I_3 based on the data of 2023.

Port	Ice Days (d/m.)	Low Water (d/m.)	Floods (d/m.)	Current > 2 m/s (d/m.)	D_{restr}	I_3
Klaipėda	30	70	0	0	100	0.726
Gdańsk	20	40	10	10	80	0.781
Gdynia	-	-	-	-	-	0
Tallinn	-	-	-	-	-	0
Riga	-	-	-	-	-	0
Szczecin	20	0	5	5	30	0.918
HaminaKotka	55	0	0	0	55	0.849

Table A3. Calculation of I_5 based on the data of 2023.

Port Hinterland	Inland Terminals	Terminal Capacity C_Term (t/m.)	IWT Cargo Flow F_IWT (t/m.)	I_5
Klaipėda	Kauno, Jurbarkas Terminals	500,000	162,000	3.086
Gdańsk	Bydgoszcz Terminal	2,000,000	414,000	4.831
Gdynia	-	-	-	0
Tallinn	-	-	-	0
Riga	-	-	-	0
Szczecin	Terminals on the Lower Odra	3,000,000	1,275,000	2.353
HaminaKotka *	Saimaa Ports	1,220,000	826,000	1.477

* Note: HaminaKotka data is for 2022, as navigation was suspended in 2023 due to the war with Russia.

References

1. European Parliamentary Research Service. *Inland Waterway Transport in the EU*; Briefing PE 698.918; European Parliament: Brussels, Belgium, 2022. Available online: [https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698918/EPRS_BRI\(2022\)698918_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698918/EPRS_BRI(2022)698918_EN.pdf) (accessed on 20 March 2026).
2. European Commission. *Communication on the EU Industrial Maritime Strategy (COM(2026) 111 Final)*; European Commission: Brussels, Belgium, 2026. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52026DC0111> (accessed on 20 March 2026).
3. Calderón-Rivera, N.; Bartusevičienė, I.; Ballini, F. Barriers and Solutions for Sustainable Development of Inland Waterway Transport: A Literature Review. *Transp. Econ. Manag.* **2024**, *2*, 31–44. [CrossRef]
4. Zhang, L.; Liu, Q.; Mathisen, T.A.; Ge, Y.E. Navigating Environmental Sustainability in Inland Waterway Transport: Emission Challenges and Solutions. *Marit. Policy Manag.* **2025**, *53*, 625–649. [CrossRef]
5. Eurostat. *Freight Transport Statistics—Modal Split; Statistics Explained; Dataset Code: Tran_hv_ms_frmod*; European Commission: Luxembourg, 2024. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split (accessed on 20 March 2026).

6. EMMA Project Consortium. *Competitiveness Improvement Plan: Enhancing Inland Waterway Transport Activity in the Baltic Sea Region*; Interreg Baltic Sea Region Programme: Hamburg, Germany, 2020. Available online: https://interreg-baltic.eu/wp-content/uploads/2021/10/20-EMMA_Competitiveness_improvement_plan_for_inland_waterway_shipping.pdf (accessed on 20 March 2026).
7. Calderón-Rivera, N.; Bartusevičienė, I.; Ballini, F. Sustainable Development of Inland Waterways Transport: A Review. *J. Shipp. Trade* **2024**, *9*, 3. [\[CrossRef\]](#)
8. Jayakodi, J.M.R.S.; Othayoth, D.; Rameesha, T.V.; Kini, B.A. Assessing the Level of Sustainable Integration between Inland Water Transport and Other Modes. *Case Stud. Transp. Policy* **2025**, *22*, 101624. [\[CrossRef\]](#)
9. van Dorsser, C. Existing Waterway Infrastructures and Future Needs. In *Inland Waterway Transport Challenges and Prospects*; Wiegman, B., Konings, R., Eds.; Routledge: London, UK, 2022; pp. 99–124.
10. Jiang, X.; Zhan, Z.; Ren, W.; Tao, X.; Zheng, S.; Luo, M. Balancing Economic and Environmental Strategies in Regional Hinterland Transport: A Dynamic Network Cross Efficiency Analysis. *Transp. Policy* **2025**, *162*, 128–154. [\[CrossRef\]](#)
11. Notteboom, T.E.; Rodrigue, J.P. Port Regionalization: Towards a New Phase in Port Development. *Marit. Policy Manag.* **2005**, *32*, 297–313. [\[CrossRef\]](#)
12. Rodrigue, J.P.; Comtois, C.; Slack, B. *The Geography of Transport Systems*, 4th ed.; Routledge: New York, NY, USA, 2016.
13. Behdani, B.; Wiegman, B.; Roso, V.; Haralambides, H. Port-Hinterland Transport and Logistics: Emerging Trends and Frontier Research. *Marit. Econ. Logist.* **2020**, *22*, 1–25. [\[CrossRef\]](#)
14. Guerrero, D. Impacts of Transport Connections on Port Hinterlands. *Reg. Stud.* **2019**, *53*, 540–549. [\[CrossRef\]](#)
15. Locaitienė, V.; Čižiūnienė, K. Assessing the Logistics Efficiency of Baltic Region Seaports Through DEA-BCC and Spatial Analysis. *J. Mar. Sci. Eng.* **2025**, *13*, 50. [\[CrossRef\]](#)
16. Franc, P.; Van der Horst, M. Understanding Hinterland Service Integration by Shipping Lines and Terminal Operators: A Theoretical and Empirical Analysis. *J. Transp. Geogr.* **2010**, *18*, 557–566. [\[CrossRef\]](#)
17. Notteboom, T.E.; Parola, F.; Satta, G. The Relationship between Transshipment Incidence and Throughput Volatility in North European and Mediterranean Container Ports. *J. Transp. Geogr.* **2019**, *74*, 371–381. [\[CrossRef\]](#)
18. Xu, L.; Shen, C.; Chen, J.; Pan, X.; Xiao, G. Efficiency Evaluation and Improvement Pathway of Sulfur-Oxide Emissions in European Ports Based on Context-Dependent SBM-DEA Model. *Mar. Pollut. Bull.* **2024**, *208*, 117002. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Guo, T.; Liu, P.; Wang, C.; Xie, J.; Du, J.; Lim, M.K. Toward Sustainable Port-Hinterland Transportation: A Holistic Approach to Design Modal Shift Policy Mixes. *Transp. Res. Part A Policy Pract.* **2023**, *174*, 103746. [\[CrossRef\]](#)
20. Hasan, K.R.; Zhang, W.; Shi, W. A Sustainable Port-Hinterland Container Transport System: The Simulation-Based Scenarios for CO₂ Emission Reduction. *Sustainability* **2023**, *15*, 12944. [\[CrossRef\]](#)
21. Drożdż, W.; Miśkiewicz, R.; Pomianowski, A. Modern Types of Propulsion for Inland Waterway Transport as a Response to Contemporary Challenges in the Logistics Chain across Polish Seaports. *Sustainability* **2023**, *15*, 15254. [\[CrossRef\]](#)
22. Kalajdžić, M.; Vasilev, M.; Momčilović, N. Evaluating an Inland Waterway Cargo Vessel's Energy Efficiency Indices. *Pol. Marit. Res.* **2022**, *29*, 14–23. [\[CrossRef\]](#)
23. Paulauskas, V.; Henesey, L.; Plačienė, B.; Jonkus, M.; Paulauskas, D.; Barzdžiukas, R.; Kaulitzky, A.; Simutis, M. Optimizing Transportation between Sea Ports and Regions by Road Transport and Rail and Inland Waterway Transport Means Including “Last Mile” Solutions. *Appl. Sci.* **2022**, *12*, 10652. [\[CrossRef\]](#)
24. Bu, F.; Heather Nachtmann, M.; Chimka, J.R. *Modeling Dynamic Behavior of Navigable Inland Waterways*; University of Arkansas: Fayetteville, AR, USA, 2024.
25. Malkus, R.; Liebuviene, J.; Jokubynienė, V. Inland Water Transport Applicability for Sustainable Sea Port Hinterland Infrastructure Development. Klaipėda Sea-Port Case. *Transp. Probl.* **2020**, *15*, 25–31. [\[CrossRef\]](#)
26. Anton, C.; Gasparotti, C.; Rusu, E. A Challenge for the Inland Navigation—A Connection between the Baltic and the Black Seas. In *Proceedings of the International Conference on Traffic and Transport Engineering, Belgrade, Serbia, 27–28 September 2018*; City Net Scientific Research Center Ltd.: Belgrade, Serbia, 2018. Available online: http://ijtte.com/uploads/news_files/ICTTE%20Belgrade%202018_Proceedings.pdf (accessed on 2 April 2026).
27. Medyna, P.; Sobkowicz, P. Hydrographic and Navigational Analysis of Lower Order Shipping Conditions—Case Study of the Backflow Occurrence. *EDP Sci.* **2017**, *17*, 7. [\[CrossRef\]](#)
28. Plotnikova, E.; Vienažindienė, M.; Slavinskas, S. Development of Inland Waterway Transport as a Key to Ensure Sustainability: A Case Study of Lithuania. *Sustainability* **2022**, *14*, 10532. [\[CrossRef\]](#)
29. Gerlitz, L.; Meyer, C.; Henesey, L. Sourcing Sustainability Transition in Small and Medium-Sized Ports of the Baltic Sea Region: A Case of Sustainable Futuring with Living Labs. *Sustainability* **2024**, *16*, 4667. [\[CrossRef\]](#)
30. Gbako, S.; Paraskevadakis, D.; Ren, J.; Wang, J.; Radmilovic, Z. A Systematic Literature Review of Technological Developments and Challenges for Inland Waterways Freight Transport in Intermodal Supply Chain Management. *Benchmark. Int. J.* **2025**, *32*, 398–431. [\[CrossRef\]](#)

31. Gucma, S.; Gucma, M.; Gralak, R.; Przywarty, M. Maximum Safe Parameters of Ships in Complex Systems of Port Waterways. *Appl. Sci.* **2022**, *12*, 7692. [CrossRef]
32. Burciu, Z. Improvement of Manoeuvring Properties of Inland Navigation Units by Using the Magnus Effect. *TransNav* **2023**, *17*, 679–684. [CrossRef]
33. United Nations Economic Commission for Europe (UNECE). *European Code for Inland Waterways (CEVNI)*, 6th ed.; United Nations: Geneva, Switzerland, 2021.
34. European Parliament; Council of the European Union. Directive (EU) 2016/1629 of the European Parliament and of the Council of 14 September 2016 laying down technical requirements for inland waterway vessels, amending Directive 2009/100/EC and repealing Directive 2006/87/EC. *Off. J. Eur. Union* **2016**, L252, 118–278. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016L1629> (accessed on 20 March 2026).
35. Bu, F.; Nachtmann, H. Literature Review and Comparative Analysis of Inland Waterways Transport: “Container on Barge”. *Marit. Econ. Logist.* **2023**, *25*, 140–173. [CrossRef]
36. World Association for Waterborne Transport Infrastructure (PIANC). *Standardisation of Inland Waterways—Proposal for the Revision of the ECMT 1992 Classification*; PIANC: Brussels, Belgium, 2020. Available online: <https://www.pianc.org/publication/standardisation-of-inland-waterways-proposal-for-the-revision-of-the-ecmt-1992-classification-2020/> (accessed on 26 March 2026).
37. United Nations Economic Commission for Europe (UNECE). *Inventory of Main Standards and Parameters of the E Waterway Network (Blue Book)*, 4th ed.; United Nations: Geneva, Switzerland, 2023.
38. United Nations Economic Commission for Europe (UNECE). *European Agreement on Main Inland Waterways of International Importance (AGN)*; United Nations: Geneva, Switzerland, 1996. Available online: <https://unece.org/fileadmin/DAM/trans/doc/2012/sc3wp3/ECE-TRANS-120r2efr-forWeb.pdf> (accessed on 2 April 2026).
39. Flitsch, V.; Brümmerstedt, K. Freight Transport Modelling of Container Hinterland Supply Chains. In *Operational Excellence in Logistics and Supply Chains: Optimization Methods, Data-Driven Approaches and Security Insights*; Blecker, T., Kersten, W., Ringle, C.M., Eds.; Hamburg University of Technology (TUHH), Institute of Business Logistics and General Management: Hamburg, Germany, 2015; Volume 22, pp. 233–266. [CrossRef]
40. Passchyn, W.; Briskorn, D.; Spijksma, F.C.R. Mathematical Programming Models for Lock Scheduling with an Emission Objective. *Eur. J. Oper. Res.* **2016**, *248*, 802–814. [CrossRef]
41. Zhao, K.; Jin, J.G.; Zhang, D.; Ji, S.; Lee, D.H. A Variable Neighborhood Search Heuristic for Real-Time Barge Scheduling in a River-to-Sea Channel with Tidal Restrictions. *Transp. Res. Part E Logist. Transp. Rev.* **2023**, *179*, 103280. [CrossRef]
42. Shobayo, P.; Bedoya-Maya, F.; van Hassel, E.; Vanelander, T.; Christopoulou, E.; Majoor, I. Assessing Inland Waterway Transport (IWT) Container Logistics on the Rhine–Alpine Corridor: A Discrete Event Simulation Approach. *Res. Transp. Econ.* **2024**, *107*, 101475. [CrossRef]
43. Notteboom, T.; Pallis, A.; Rodrigue, J.-P. *Port Economics, Management and Policy*; Routledge: London, UK, 2021. Available online: <https://porteconomicsmanagement.org/> (accessed on 2 April 2026).
44. Gong, H.; Matala, R. A Study of Full-Scale Measurement of Channel Widening by IB Polaris. In *Proceedings of the 32nd International Ocean and Polar Engineering Conference (ISOPE), Shanghai, China, 5–10 June 2022*; Paper No. ISOPE-I-22-341; ISOPE: Mountain View, CA, USA, 2022. Available online: <https://onepetro.org/ISOPEIOPEC/ISOPE22/conference/ISOPE22> (accessed on 2 April 2026).
45. Gbako, S.; Paraskevadakis, D.; Ren, J.; Wang, J. Sustainable River-Sea Freight Transport in Major Logistic Gateways: A Socio-Economic and Environmental Performance Evaluation of the United Kingdom’s and Continental Europe’s Inland Waterway Transport. *Manag. Environ. Qual. Int. J.* **2025**, *36*, 1478–1519. [CrossRef]
46. Gbako, S.; Paraskevadakis, D.; Ren, J.; Wang, J. Digitalisation and Decarbonisation Challenges of Inland Waterways Freight Logistics Transport and Their Integration into Regional Supply Chains—A Case Study. *Logist. Supply Chain. Sustain. Glob. Chall.* **2023**, *14*, 1–23. [CrossRef]
47. Durajczyk, P. The Analysis of the Possibility to Improve the Efficiency of Container Transport via the Oder Waterway with the Use of the RIS System. *Nase More* **2020**, *67*, 143–148. [CrossRef]
48. Niedzielski, P.; Durajczyk, P.; Drop, N. Utilizing the RIS System to Improve the Efficiency of Inland Waterway Transport Companies. *Procedia Comput. Sci.* **2021**, *192*, 3486–3495. [CrossRef]
49. Durajczyk, P.; Drop, N. Possibilities of Using Inland Navigation to Improve Efficiency of Urban and Interurban Freight Transport with the Use of the River Information Services (RIS) System—Case Study. *Energies* **2021**, *14*, 7086. [CrossRef]
50. Specht, P.; Bamler, J.N.; Jović, M.; Meyer-Larsen, N. Digital Information Services Needed for a Sustainable Inland Waterway Transportation Business. *Sustainability* **2022**, *14*, 6392. [CrossRef]
51. Meyer, C. Integration of Baltic Small and Medium-Sized Ports in Regional Innovation Strategies on Smart Specialisation (RIS3). *J. Open Innov. Technol. Mark. Complex.* **2021**, *7*, 184. [CrossRef]
52. Meyer, C.; Gerlitz, L.; Philipp, R.; Paulauskas, V. A Digital or Sustainable Small and Medium-Sized Port? Sustainable Port Blueprint in the Baltic Sea Region Based on Port Benchmarking. *Transp. Telecommun.* **2021**, *22*, 332–342. [CrossRef]

53. Ludden, V.; Wrona, K.; Jansen, L.; Colaiacomo, E.; Verbergh, E.; Vanelslender, T.; van Hassel, E.; Hoet, L. *Study Supporting the Evaluation of Directive 2005/44/EC on Harmonised River Information Services (RIS)*; European Commission, Directorate-General for Mobility and Transport: Brussels, Belgium, 2020. Available online: <https://transport.ec.europa.eu/> (accessed on 2 April 2026).
54. James, K.J.; Shenoy, V.V.; Bhasi, M.; Nandakumar, C.G. Automated ICT Systems in Inland Waterways by Developing a Multiflow River Information Services System. *Int. J. Adv. Res. Eng. Technol.* **2019**, *10*, 381–392. [\[CrossRef\]](#)
55. Tubis, A.A.; Skupień, E.T.; Jędrzychowski, K.K.; Jędrzychowski, H. A Sector-Specific Digital Maturity Model for Inland Waterway Transport. *Systems* **2025**, *13*, 347. [\[CrossRef\]](#)
56. Braekers, K.; Caris, A.; Janssens, G.K. Optimal Shipping Routes and Vessel Size for Intermodal Barge Transport with Empty Container Repositioning. *Comput. Ind.* **2013**, *64*, 155–164. [\[CrossRef\]](#)
57. Hervás-Peralta, M.; Poveda-Reyes, S.; Molero, G.D.; Santarremigia, F.E.; Pastor-Ferrando, J.P. Improving the Performance of Dry and Maritime Ports by Increasing Knowledge about the Most Relevant Functionalities of the Terminal Operating System (TOS). *Sustainability* **2019**, *11*, 1648. [\[CrossRef\]](#)
58. Surucu-Balci, E.; Iris, Ç.; Balci, G. Digital information in maritime supply chains with blockchain and cloud platforms: Supply chain capabilities, barriers, and research opportunities. *Technol. Forecast. Soc. Change* **2024**, *198*, 22978. [\[CrossRef\]](#)
59. European Commission. *NALADES III: Boosting Future-Proof European Inland Waterway Transport (COM(2021) 324 Final)*; European Commission: Brussels, Belgium, 2021. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0324> (accessed on 20 April 2026).
60. Perčić, M.; Vladimir, N.; Fan, A. Techno-Economic Assessment of Alternative Marine Fuels for Inland Shipping in Croatia. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111363. [\[CrossRef\]](#)
61. Zhu, S.; Gao, J.; He, X.; Zhang, S.; Jin, Y.; Tan, Z. Green Logistics Oriented Tug Scheduling for Inland Waterway Logistics. *Adv. Eng. Inform.* **2021**, *49*, 101323. [\[CrossRef\]](#)
62. Tan, Z.; Li, W.; Zhang, X.; Yang, H. Service Charge and Capacity Selection of an Inland River Port with Location-Dependent Shipping Cost and Service Congestion. *Transp. Res. Part E Logist. Transp. Rev.* **2015**, *76*, 13–33. [\[CrossRef\]](#)
63. Hsu, W.K.K.; Huang, S.H.S.; Huynh, N.T. An Assessment of Operating Efficiency for Container Terminals in a Port—An Empirical Study in Kaohsiung Port Using Data Envelopment Analysis. *Res. Transp. Bus. Manag.* **2023**, *46*, 100823. [\[CrossRef\]](#)
64. Hoffmann, J.; Rodrigue, J.-P.; Sánchez, R.J.; Tavasszy, L. New Context Calls for Changing How We Measure Maritime Connectivity. *UNCTAD Transp. Trade Facil. Newsl.* **2024**, *101*, 114. Available online: <https://unctad.org> (accessed on 20 April 2026).
65. World Bank. *The Container Port Performance Index 2023: A Comparable Assessment of Performance Based on Vessel Time in Port*; World Bank: Washington, DC, USA, 2024. Available online: <https://documents1.worldbank.org/curated/en/099060324114539683/pdf/P17583313892300871be641a5ea7b90e0e6.pdf> (accessed on 20 April 2026).
66. United Nations Economic Commission for Europe (UNECE). *Sustainable Inland Transport Connectivity Indicators*; United Nations: Geneva, Switzerland, 2023. Available online: <https://unece.org/transport/publications/sustainable-inland-transport-connectivity-indicators> (accessed on 20 April 2026).
67. Al-Sahili, K.; Hassouna, F.M.A. National Transport Connectivity Assessment for Landlocked Area –Cross Border Transport in Palestine. *-Najah Univ. J. Res.-A (Nat. Sci.)* **2025**, *39*, 2359. [\[CrossRef\]](#)
68. Organisation for Economic Co-operation and Development (OECD); European Commission, Joint Research Centre (JRC). *Handbook on Constructing Composite Indicators: Methodology and User Guide*; OECD Publishing: Paris, France, 2008. Available online: <https://www.oecd.org/sti/42495745.pdf> (accessed on 20 April 2026).
69. Ayadi, H.; Benaissa, M.; Hamani, N.; Kermad, L. Assessing the Sustainability of Transport Systems through Indexes: A State-of-the-Art Review. *Sustainability* **2024**, *16*, 1455. [\[CrossRef\]](#)
70. Sullivan, C. Calculating a Water Poverty Index. *World Dev.* **2002**, *30*, 1195–1210. [\[CrossRef\]](#)
71. Greco, S.; Ishizaka, A.; Tasiou, M.; Torrisi, G. On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. *Soc. Indic. Res.* **2019**, *141*, 61–94. [\[CrossRef\]](#)
72. Amudha, M.; Ramachandran, M.; Saravanan, V.; Anusuya, P.; Gayathri, R. A Study on TOPSIS MCDM Techniques and Its Application. *Data Anal. Artif. Intell.* **2021**, *1*, 2. [\[CrossRef\]](#)
73. Liu, K.; Zhang, J.; Yan, X.; Liu, Y.; Zhang, D.; Hu, W. Safety Assessment for Inland Waterway Transportation with an Extended Fuzzy TOPSIS. *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.* **2016**, *230*, 215–227. [\[CrossRef\]](#)
74. Mardani, A.; Zavadskas, E.K.; Khalifah, Z.; Jusoh, A.; Nor, K. Multiple Criteria Decision-Making Techniques in Transportation Systems: A Systematic Review of the State of the Art Literature. *Transport* **2016**, *31*, 359–385. [\[CrossRef\]](#)
75. European Committee for Drawing up Standards in the Field of Inland Navigation (CESNI). *European Standard for Qualifications in Inland Navigation (ES-QIN)*; CESNI: Strasbourg, France, 2018. Available online: <https://www.cesni.eu/en/standards/es-qin/> (accessed on 3 April 2026).
76. Lietuvos Respublikos Duomenų Portalas; Vidaus Vandens Kelių Direkcija. Vidaus Vandens Kelių Transporto Duomenys. Available online: https://data.gov.lt/datasets/2077/?resource_version=2442 (accessed on 18 April 2026).

77. Instytut Meteorologii i Gospodarki Wodnej—Państwowy Instytut Badawczy (IMGW-PIB). Hydrological Data and Water Level Monitoring—Vistula and Oder River Basins. Available online: <https://hydro.imgw.pl/> (accessed on 20 March 2026).
78. Latvijas Vides, Ģeoloģijas un Meteoroloģijas Centrs (LVĢMC). Plūdu Riska Informācijas Sistēma—Flood Risk Information System. Available online: <https://videscentrs.lvģmc.lv/iebuve/pludu-riska-informacijas-sistema> (accessed on 20 March 2026).
79. Väylävirasto (Finnish Transport Infrastructure Agency). Saimaa Canal—Navigation Data, Vessel Dimensions and Traffic Season. Available online: <https://vayla.fi/en/transport-network/waterways/canals-and-bridges/the-saimaa-canal/navigation-in-the-saimaa-canal-and-lake-saimaa> (accessed on 20 March 2026).
80. Państwowe Gospodarstwo Wodne Wody Polskie—Regionalny Zarząd Gospodarki Wodnej w Szczecinie (RZGW Szczecin). Sytuacja Hydrologiczno-Nawigacyjna—Hydrological and Navigation Situation Reports. Available online: <https://szczecin.wody.gov.pl/sytuacja-hydrologiczno-nawigacyjna> (accessed on 20 March 2026).
81. ten Hove, D.; Koedijk, O.C. Guidelines for Inland Waterways in Rivers. In Proceedings of the Smart Rivers 2019 Conference, Lyon, France, 30 September–3 October 2019. Available online: <https://www.marin.nl/en/publications/guidelines-for-inland-waterways-in-rivers> (accessed on 24 May 2026).
82. European Parliament; Council of the European Union. Directive 2005/44/EC of the European Parliament and of the Council of 7 September 2005 on Harmonised River Information Services (RIS) on Inland Waterways in the Community. *Off. J. Eur. Union* **2005**, L255, 152–159. Available online: <https://eur-lex.europa.eu/eli/dir/2005/44/oj> (accessed on 3 May 2026).
83. Lithuanian Inland Waterways Authority. 2022–2025 Strategic Activity Plan; Vidaus Vandens Kelių Direkcija: Vilnius, Lithuania, 2022. Available online: <https://vvkd.lt/wp-content/uploads/2022/02/VI-VVKD2022-2025SVP.pdf> (accessed on 20 March 2026).
84. Eurostat. Freight Transport by Inland Waterways—Goods Transported by Type of Good; Dataset: *iww_go_atygo*; European Commission: Luxembourg, 2024. Available online: https://ec.europa.eu/eurostat/databrowser/view/iww_go_atygo/default/table (accessed on 20 March 2026).
85. Statistics Poland (Główny Urząd Statystyczny, GUS). Transport—Inland Waterway Transport Statistics. Available online: <https://stat.gov.pl/en/topics/transport-and-communications/transport/> (accessed on 20 March 2026).
86. Regionalny Zarząd Gospodarki Wodnej w Gdańsku (RZGW Gdańsk). Hydrological Data—Vistula River Basin. Available online: <https://www.gov.pl/web/wody-polskie-gdansk> (accessed on 20 March 2026).
87. Statistics Finland. Waterway Transport Statistics—Goods Transported by Inland Waterways; Dataset: *statfin_kvliik_pxt_12il.px*; Statistics Finland: Helsinki, Finland, 2023. Available online: https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_kvliik/statfin_kvliik_pxt_12il.px (accessed on 20 March 2026).
88. Państwowe Gospodarstwo Wodne Wody Polskie—Regionalny Zarząd Gospodarki Wodnej w Szczecinie (RZGW Szczecin). Inland Waterway Infrastructure Data—Odra River Corridor. Available online: <https://szczecin.wody.gov.pl/> (accessed on 20 March 2026).
89. Kubiak-Wójcicka, K.; Manoiu, V.-M. International Inland Waterways in Poland: Current State and Their Importance in EU Transport Policy. *Water* **2025**, *17*, 3190. [CrossRef]
90. Durajczyk, P.; Drop, N.; Niedzielski, P. Possibilities of Using Inland Navigation to Improve the Efficiency of Interurban Freight Transport with the Use of the RIS System—Case Study of the Route Opole–Szczecin. *Sustainability* **2024**, *16*, 10754. [CrossRef]
91. Roso, V.; Vural, C.; Abrahamsson, A.; Engström, M.; Rogerson, S.; Santén, V. Drivers and Barriers for Inland Waterway Transportation. *Oper. Supply Chain. Manag. Int. J.* **2020**, *13*, 406–417. [CrossRef]
92. Caris, A.; Macharis, C.; Janssens, G.K. Decision Support in Intermodal Transport: A New Research Agenda. *Comput. Ind.* **2013**, *64*, 105–112. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.