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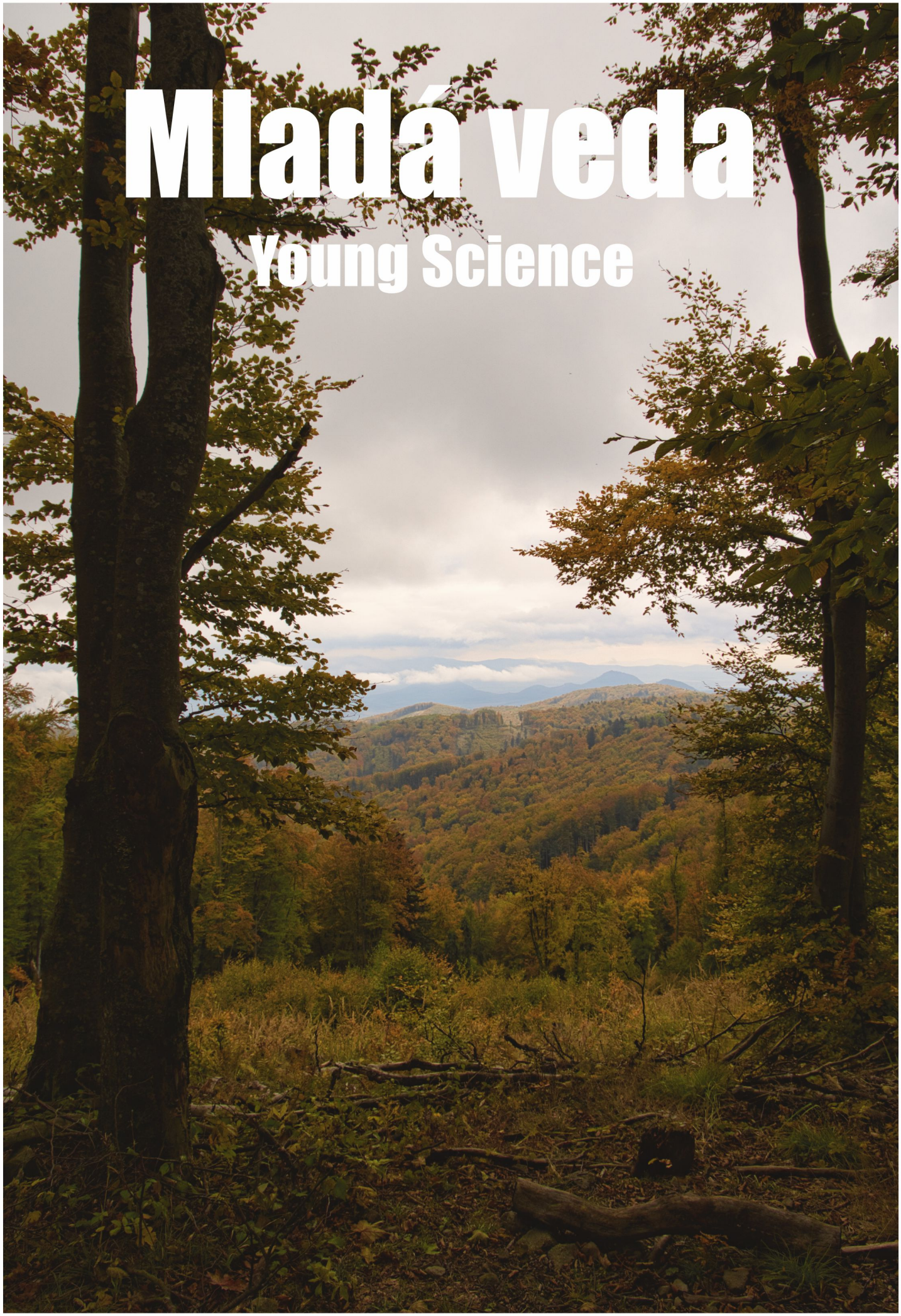

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LOW WATER LEVELS ON EUROPEAN INLAND WATERWAYS: OPERATIONAL, LOGISTICAL AND SAFETY IMPLICATIONS

NÍZKE VODNÉ STAVY NA EURÓPSKYCH VNÚTROZEMSKÝCH VODNÝCH CESTÁCH: PREVÁDZKOVÉ, LOGISTICKÉ A BEZPEČNOSTNÉ DÔSLEDKY

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Autorka pôsobí ako externá doktorandka na Fakulte prevádzky a ekonomiky dopravy a spojov Žilinskej univerzity v Žiline. Vo svojom výskume sa zameriava na problematiku simulačného výcviku lodných posádok, výkonovej analytiky a návrhu adaptívnych výcvikových systémov vo vnútrozemskej vodnej doprave.

Abstract

Low water levels represent a significant factor affecting the reliability and efficiency of inland waterway transport in Europe. A decline in water levels and the related reduction in available navigable depth may lead to limitations in the permissible draught of vessels, reduced utilisation of available transport capacity, and deterioration of conditions for safe and uninterrupted navigation. The consequences of low-water periods therefore affect not only vessel operations themselves, but also transport organisation, the reliability of logistics chains, and navigation safety. The article focuses on assessing the impact of low water levels on selected European inland waterways, with particular emphasis on their operational, logistical, and safety-related consequences. Attention is primarily paid to the relationship between hydrological and navigation conditions, available navigable depth, vessel draught, and the possibilities for utilising vessel transport capacity. The study also includes a comparative assessment of selected European inland waterways with the aim of identifying the main consequences of low-water periods for inland waterway transport. The study highlights the importance of systematic assessment of low water levels in ensuring operational reliability, effective transport planning, and navigation safety on European inland waterways.

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Key words: low water levels, inland waterway transport, navigable depth, vessel draught, transport capacity, navigation safety

Abstrakt
Nízke vodné stavy predstavujú významný faktor ovplyvňujúci spoľahlivosť a efektívnosť vnútrozemskej vodnej dopravy v Európe. Pokles vodných stavov a s ním súvisiace obmedzenie dostupnej plavebnej hĺbky môže viesť k znižovaniu prípustného ponoru plavidiel, obmedzeniu využiteľnej prepravnej kapacity a k zhoršeniu podmienok pre bezpečnú a plynulú plavbu. Dôsledky nízkovodných období sa preto neprejavujú iba v samotnej prevádzke plavidiel, ale zasahujú aj do organizácie prepravy, spoľahlivosti logistických reťazcov a bezpečnosti plavby. Článok sa zameriava na hodnotenie vplyvu nízkych vodných stavov na vybrané európske vnútrozemské vodné cesty so zreteľom na ich prevádzkové, logistické a bezpečnostné dôsledky. Pozornosť je venovaná najmä vzťahu medzi hydrologickými a plavebnými podmienkami, dostupnou plavebnou hĺbkou, ponorom plavidiel a možnosťami využitia ich prepravnej kapacity. Súčasťou štúdie je komparatívne posúdenie vybraných európskych vodných ciest s cieľom identifikovať hlavné dôsledky nízkovodných období pre vnútrozemskú vodnú dopravu. Štúdia poukazuje na význam systematického hodnotenia nízkych vodných stavov pri zabezpečovaní prevádzkovej spoľahlivosti, efektívneho plánovania prepravy a bezpečnosti plavby na európskych vnútrozemských vodných cestách.
Kľúčové slová: nízke vodné stavy, vnútrozemská vodná doprava, plavebná hĺbka, ponor plavidla, prepravná kapacita, bezpečnosť plavby

Introduction

Inland waterway transport represents an important component of the European transport system, particularly in the transport of large volumes of goods over medium and long distances. Its operational efficiency is closely linked to the navigability of inland waterways and therefore depends significantly on current hydrological conditions. Sufficient navigable depth is one of the fundamental prerequisites for maintaining the required vessel draught, efficient utilisation of transport capacity, and continuity of navigation.

Low water levels represent a significant operational challenge for inland navigation. A decline in water level may lead to a reduction in available navigable depth and consequently to restrictions on the permissible draught of vessels. Under such conditions, vessels may be unable to utilise their full carrying capacity, which can result in reduced cargo volumes, an increased number of voyages required to transport the same quantity of goods, and changes in transport planning. Prolonged low-water periods may therefore affect not only vessel operations themselves but also the efficiency and reliability of logistics chains connected to inland waterway transport.

The impact of low water levels is particularly significant on major European inland waterways, where navigation conditions differ depending on hydrological characteristics, fairway parameters, technical infrastructure, and local navigation conditions. The Rhine, Danube, and Elbe represent important European inland waterways on which variations in hydrological conditions may directly affect vessel operations and the continuity of freight

transport. A comparative assessment of these waterways can provide a broader understanding of the consequences of low-water periods within the European inland navigation system.

In addition to operational and logistical impacts, low water levels also have an important safety dimension. Reduced navigable depth increases the importance of continuous assessment of vessel draught, available water depth, and under-keel clearance. Navigation under restricted depth conditions therefore places increased demands on voyage planning, vessel handling and manoeuvring, as well as on the professional competencies of crew members.

The main objective of this article is to assess the impact of low water levels on selected European inland waterways and to identify their operational, logistical, and safety-related consequences. Particular attention is paid to the relationship between hydrological and navigation conditions, available navigable depth, vessel draught, and transport capacity. The study also focuses on comparing the consequences of low-water periods on selected European inland waterways and identifying the main factors affecting the reliability and safety of inland waterway transport.

Low Water Levels and Navigation Conditions on European Inland Waterways

Navigation conditions on European inland waterways are closely related to hydrological conditions and the technical parameters of individual waterways. Water level variations influence the available water depth and may consequently affect the permissible draught of vessels, their loading possibilities, and the continuity of navigation. During prolonged periods of low water, these limitations may become particularly significant for freight transport on major European rivers.

From the perspective of inland navigation, it is important to distinguish between water level, water depth, and navigable depth. Water level represents the elevation of the water surface in relation to a defined reference level, while water depth describes the vertical distance between the water surface and the riverbed at a particular location. Navigable depth refers to the depth available for safe navigation within the designated fairway and represents an important parameter for determining the permissible draught of a vessel.

Another important parameter is vessel draught, which represents the vertical distance between the waterline and the lowest point of the submerged part of the vessel. The relationship between available navigable depth and vessel draught directly influences the under-keel clearance (UKC). Sufficient under-keel clearance is essential for maintaining safe navigation and reducing the risk of contact between the vessel and the riverbed.

Under low-water conditions, a reduction in available navigable depth may require a reduction in vessel draught. For cargo vessels, this is generally achieved by limiting the amount of cargo carried. Consequently, a vessel that would normally operate close to its maximum carrying capacity may only be able to utilise part of its available capacity during low-water periods. The hydrological situation can therefore directly affect both the technical conditions of vessel operation and the economic efficiency of inland waterway transport.

The effects of low water levels may differ considerably between European inland waterways due to differences in river morphology, hydrological regimes, fairway characteristics, waterway infrastructure, and navigation management. The Rhine, Danube, and

Elbe represent important European inland waterways with different navigation conditions and therefore provide a suitable basis for comparative assessment of the operational consequences of low-water periods.

The relationship between water level, navigable depth, vessel draught, and under-keel clearance represents one of the fundamental principles determining vessel operation under restricted depth conditions. Figure 1 illustrates this relationship schematically and provides a simplified representation of the main parameters affecting safe vessel operation during low-water conditions.

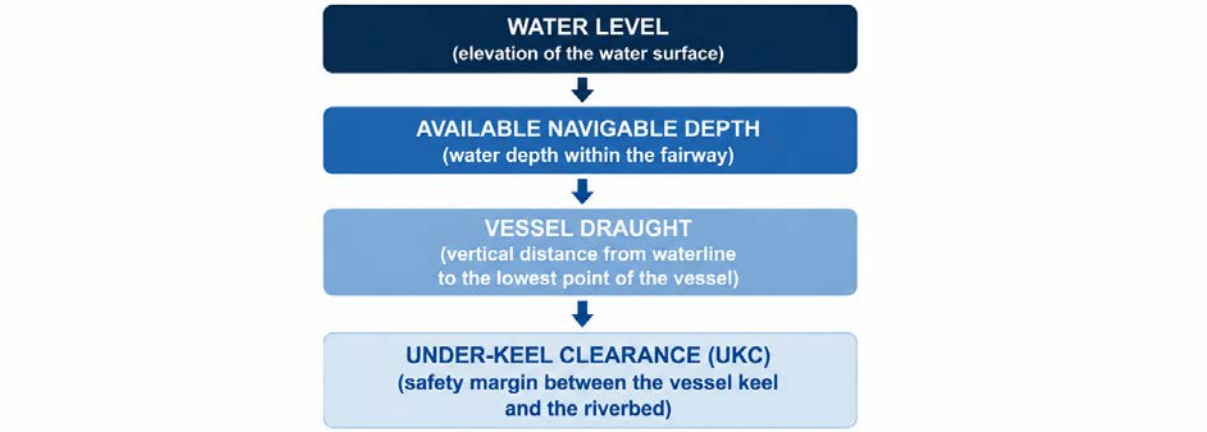

Figure 1 – Conceptual relationship between water level, navigable depth, vessel draught and under-keel clearance (UKC)
Source: author's own processing

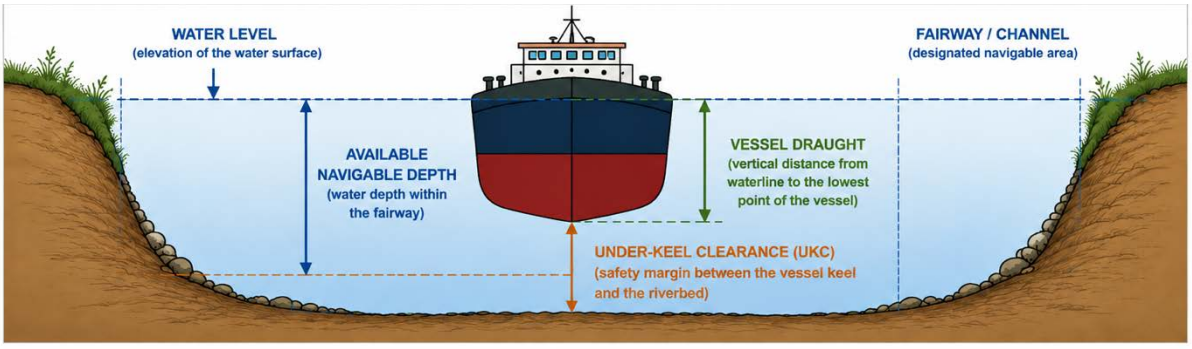

Figure 2 – Cross-section of a waterway showing the relationship between key navigation parameters
Source: author's own processing

Operational, Logistical and Safety Impacts of Low Water Levels

The consequences of low water levels in inland waterway transport extend beyond the immediate reduction in available navigable depth. Changes in hydrological conditions may initiate a sequence of interconnected effects influencing vessel operation, transport organisation, logistics reliability, and navigation safety. The relationship between these effects is particularly important because an operational restriction imposed on a vessel may subsequently generate broader consequences for the entire transport chain.

In general, the impact mechanism can be described as a sequence in which low water levels lead to reduced navigable depth, followed by restrictions on permissible vessel draught

and reduced utilisation of vessel carrying capacity. These conditions may subsequently affect transport performance and logistics planning while simultaneously increasing the requirements for safe voyage planning and vessel handling. For this reason, the consequences of low-water periods are assessed in the following sections from three interconnected perspectives: operational, logistical, and safety-related.

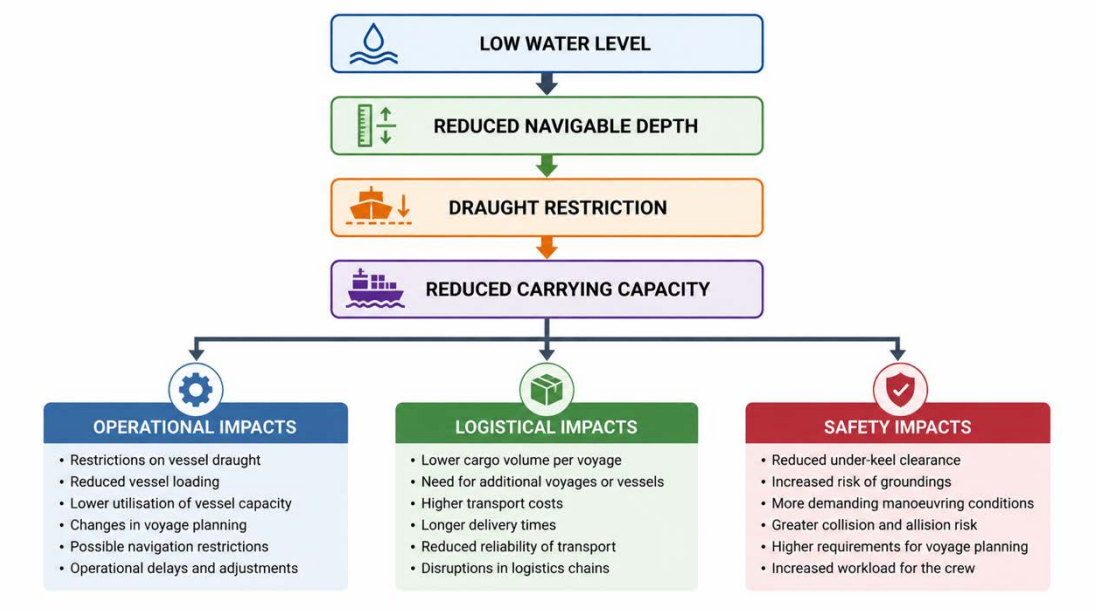

Figure 3 – Impact Chain of Low Water Levels on Inland Waterway Transport
Source: author's own processing

Operational Impacts

The most immediate operational consequence of low water levels is the reduction in available navigable depth, which may restrict the permissible draught of vessels. Since the draught of a cargo vessel is directly related to its loading condition, operators may be required to reduce the amount of cargo carried in order to comply with the depth limitations of a particular waterway section. Consequently, vessels may operate below their maximum carrying capacity even when sufficient cargo demand is available.

The extent of operational restrictions depends on several factors, including the characteristics of the waterway, fairway depth, vessel dimensions, loading condition, and the duration and severity of the low-water period. Particular attention must be paid to critical sections of a waterway where available depth may become a limiting factor for navigation. Vessel operators therefore need to continuously consider current and forecast hydrological conditions when determining loading levels and planning individual voyages. Where depth restrictions persist, adjustments to vessel deployment and voyage schedules may also become necessary.

From an operational perspective, prolonged low-water conditions may therefore reduce the effective transport performance of inland navigation. A vessel with a high nominal carrying capacity cannot provide the same transport performance when its permissible draught is restricted by the available navigable depth. The operational significance of low water levels

should consequently be assessed not only in terms of whether a waterway remains navigable, but also in terms of the extent to which vessels are able to utilise their available carrying capacity under prevailing navigation conditions.

Logistical Impacts

The operational limitations associated with low water levels can subsequently affect the performance of the entire logistics chain. When vessels are unable to utilise their full carrying capacity because of draught restrictions, the volume of cargo transported during a single voyage decreases. Maintaining the required transport volume may therefore require additional voyages, the deployment of additional vessels, or adjustments to existing transport schedules. The impact of low-water conditions thus extends beyond vessel operation and directly influences the organisation of freight transport.

Prolonged low-water periods may also affect transport costs and delivery reliability. Reduced cargo volumes per voyage can increase transport requirements per unit of cargo, while changes in vessel deployment and voyage schedules may result in longer or less predictable delivery times. Where sufficient inland waterway transport capacity cannot be maintained, shippers may need to consider alternative or complementary transport modes, particularly rail or road transport. Such adjustments may create additional requirements for transshipment, terminal operations, and coordination between individual elements of the multimodal transport chain.

From a logistics perspective, the duration and predictability of low-water conditions are therefore particularly important. Short-term restrictions may be managed through operational adjustments, whereas prolonged or recurrent low-water periods can reduce the reliability of inland waterway transport and increase uncertainty in supply-chain planning. The ability to monitor hydrological conditions, anticipate potential navigation restrictions, and adapt transport planning accordingly becomes an important factor in maintaining the continuity and resilience of logistics chains dependent on European inland waterways.

Safety Impact

Low water levels also have a significant impact on navigation safety, particularly when the available water depth approaches the draught requirements of a vessel. Under such conditions, the margin between the lowest point of the vessel and the riverbed becomes increasingly important. Maintaining sufficient under-keel clearance is therefore a fundamental consideration when assessing whether a vessel can safely navigate a particular waterway section. Reduced water depth may increase the risk of bottom contact or grounding, especially in critical sections of the fairway where the available depth is limited.

Navigation under restricted depth conditions also places increased demands on voyage planning, vessel handling, and continuous assessment of the surrounding navigation conditions. The boatmaster must consider the vessel's actual draught and loading condition together with available water depth, fairway characteristics, current conditions, vessel speed, and other traffic. Changes in water level may therefore require adjustments to the planned voyage and to vessel operation in order to maintain an adequate safety margin throughout the navigated section.

The importance of these factors is also reflected in the European competence framework for inland navigation. The practical assessment of boatmasters includes the ability to navigate and manoeuvre a vessel while taking into account water depth, the draught of the loaded vessel, and the available depth under the keel. Consequently, safe navigation during low-water periods depends not only on the technical parameters of the vessel and waterway, but also on the ability of the boatmaster and crew to correctly assess changing navigation conditions and adapt vessel operation accordingly.

Comperative Assessment of Low-Water Conditions on Selected European Inland Waterways

The practical consequences of low-water conditions vary between European inland waterways due to differences in hydrological regimes, fairway characteristics, waterway infrastructure, and navigation conditions. To identify both common and waterway-specific impacts, the Rhine, Danube, and Elbe were selected for comparative assessment. These waterways represent important components of the European inland navigation network and provide different conditions for analysing the relationship between low water levels and the operational reliability of inland waterway transport.

The comparative assessment focuses primarily on the occurrence and duration of low-water conditions, relevant navigation reference levels, limitations affecting navigable depth and vessel draught, and the resulting operational consequences. Since water-level measurements at individual gauges are related to local reference systems, absolute gauge values cannot be directly compared between different waterways. The assessment therefore focuses on the significance of low-water conditions for navigation and on the resulting restrictions affecting vessel operation and transport capacity.

Rhine

The Rhine represents one of the principal inland waterways for freight transport in Europe and is particularly important for the connection of major industrial and logistics regions with the seaports of the North Sea. Its free-flowing sections are, however, directly influenced by variations in hydrological conditions, and prolonged low-water periods may significantly affect the conditions under which freight vessels can operate.

For the assessment of low-water navigation conditions on the Rhine, the Equivalent Water Level (EWL) represents an important reference parameter. The EWL is determined by the Central Commission for the Navigation of the Rhine (CCNR) for a number of gauge stations along the river and is periodically updated to reflect long-term hydrological conditions. The current EWL 2022 has been applicable since 1 January 2023 and remains valid until the end of 2031. It represents the water level corresponding to an equivalent low-water discharge that is statistically undershot on 20 ice-free days per year.

Kaub, located on the Middle Rhine, represents an important reference gauge for assessing low-water navigation conditions. The current EWL 2022 at Kaub is 77 cm. The Middle Rhine is particularly relevant for the assessment of navigation restrictions because available fairway depth in this section can become a limiting factor for the permissible draught of cargo vessels during periods of low water. It is important to note that the gauge

reading itself does not represent the actual navigable depth. Instead, it serves as a reference parameter used together with the characteristics of the fairway when determining the depth available for navigation.

Historical observations demonstrate that severe low-water periods are not an exceptional phenomenon on the Rhine. The low-water event of 2018 had particularly significant consequences for inland navigation, while another substantial low-water period occurred in 2022. According to CCNR analyses, the discharge at Kaub remained below the equivalent low-water discharge threshold for 107 days in 2018 and for 41 days in 2022. These events illustrate the potential duration of navigation restrictions under severe hydrological conditions.

The operational consequences of low water on the Rhine are primarily reflected in restrictions on vessel draught and consequently in reduced utilisation of carrying capacity. As the available navigable depth decreases, cargo vessels may continue to navigate but with reduced loading. Unlike high-water situations, low water on the Rhine is not associated with a general water-level threshold at which navigation is automatically prohibited. The decision whether a particular section can be safely navigated under reduced water-level conditions remains dependent on the actual navigation conditions and the assessment of the vessel's skipper.

The Rhine therefore provides a relevant example of a waterway where low-water conditions may not necessarily result in a complete interruption of navigation but can substantially reduce the operational performance of inland waterway transport. The relationship between water level, available navigable depth, permissible vessel draught, and carrying capacity is consequently essential for assessing the practical effects of low-water periods on Rhine navigation.

Danube

The Danube represents one of the most important inland waterways in Europe and forms a major transport axis connecting Central and South-Eastern Europe. Due to its considerable length and the diversity of its hydrological and morphological conditions, the effects of low water levels are not uniform along the entire navigable waterway. Navigation conditions may differ substantially between the Upper, Middle, and Lower Danube, particularly with regard to available fairway depth and the occurrence of critical sections during low-water periods.

An important reference parameter for the assessment of navigation conditions on the Danube is the Low Navigable Water Level (LNWL). Periods during which water levels approach or fall below the relevant low-navigation reference values are particularly important for freight navigation, as the available fairway depth may become insufficient for vessels operating at their usual draught. Under such conditions, vessel operators may be required to reduce loading and adapt the operational draught to the available navigation conditions.

Recent navigation conditions demonstrate the practical significance of this relationship. During the first quarter of 2025, relatively stable water availability generally allowed continuous navigation on the Danube. However, during the second quarter, water levels decreased considerably. On the Upper Danube, water levels episodically fell below the LNWL during the second half of May and subsequently in June. On the Lower Danube, a

substantial decline in water levels from late June resulted in a significant reduction in permissible operating draughts and, on certain sections, temporary interruptions of navigation. The operational effects of low-water conditions are particularly visible in sections where available fairway depth becomes a limiting factor for vessel loading. Reduced permissible draught directly affects the quantity of cargo that can be transported by an individual vessel and consequently reduces the effective carrying capacity of inland waterway transport. The impact may be further intensified when low-water conditions persist for longer periods or simultaneously affect several critical sections of the waterway.

The Danube therefore demonstrates that the impact of low water levels cannot be assessed solely on the basis of water-level values at an individual gauge. A broader assessment of fairway conditions, available navigable depth, permissible vessel draught, and the spatial distribution of critical sections is necessary. The variability of navigation conditions along the Upper, Middle, and Lower Danube also highlights the importance of continuous hydrological monitoring and coordinated fairway management for maintaining reliable inland navigation during low-water periods.

Elbe

The Elbe represents an important inland waterway connecting the Czech Republic and Germany with the North Sea region. In contrast to regulated and canalised waterways, large sections of the Elbe remain strongly dependent on natural hydrological conditions. This makes navigation particularly sensitive to periods of low discharge and reduced water levels, which may significantly limit the available fairway depth and consequently restrict vessel draught and transport capacity.

Low-water conditions on the Elbe are characterised by considerable spatial variability along the waterway. Navigation conditions differ between the Czech and German sections as well as between the upper, middle, and lower reaches of the river. During prolonged periods of low discharge, critical sections may develop where the available fairway depth becomes insufficient for vessels operating at their usual draught. In such situations, vessel loading must be adapted to the actual hydrological and fairway conditions.

Recent observations confirm the continuing relevance of low-water events on the Elbe. In summer and autumn 2025, the German Federal Institute of Hydrology initiated its extreme-event monitoring programme after water discharge remained persistently below defined trigger thresholds at the reference gauges Barby and Schöna. Similar low-water conditions were again recorded in 2026, demonstrating the recurrent character of hydrological restrictions on the waterway.

Operational restrictions during low-water periods may include reductions in available fairway depth, modified fairway information, and limitations affecting vessel draught. Official navigation notices issued for the Elbe in 2026 included restrictions on fairway depth in specific river sections and temporary suspension of depth measurements and fairway-depth information because of low-water conditions. These measures illustrate the direct relationship between hydrological conditions and the operational reliability of navigation on the Elbe.

The Elbe therefore represents a waterway where low-water conditions can have a particularly significant influence on navigation performance. Reduced fairway depth affects

vessel loading possibilities and may reduce the reliability and competitiveness of inland waterway transport. Continuous monitoring of water levels, discharge, and fairway conditions is therefore essential for voyage planning and for maintaining safe and efficient navigation during prolonged low-water periods.

Comparative Assessment

The comparative assessment of the Rhine, Danube, and Elbe demonstrates that low-water conditions represent a common operational challenge for European inland waterway transport, although their practical consequences differ according to the hydrological and navigational characteristics of individual waterways. Direct comparison of absolute gauge values is not appropriate because water-level measurements are related to different local reference systems. The comparison therefore focuses on the operational significance of low-water conditions, their duration, and their impact on navigable depth, vessel draught, transport capacity, and continuity of navigation.

The Rhine demonstrates a high sensitivity of freight transport performance to prolonged low-water periods, particularly in critical sections of the Middle Rhine. Navigation may remain possible even under considerably reduced water levels, but restrictions on permissible vessel draught can substantially reduce the amount of cargo transported per voyage. The events of 2018 and 2022 illustrate that the principal consequence is not necessarily a complete interruption of navigation, but rather a significant reduction in available transport capacity and economic efficiency. At Kaub, discharge remained below the relevant equivalent low-water discharge for 107 days in 2018 and 41 days in 2022.

The Danube shows greater spatial variability because navigation conditions differ significantly between its Upper, Middle, and Lower sections. Low-water periods may result in draught restrictions as well as temporary interruptions of navigation in critical sections. Conditions observed in 2025 illustrate this variability: water levels episodically fell below the Low Navigable Water Level on the Upper Danube, while the decline on the Lower Danube led to substantial reductions in permissible operating draughts and temporary suspensions of navigation in some sections. On the Bulgarian section, 116 days below LNWL were recorded in 2025, compared with 111 days in 2022, confirming the severity of recent low-water conditions.

The Elbe differs from the Rhine and Danube because large free-flowing sections remain particularly dependent on natural discharge conditions. Recurrent low-water events may therefore significantly reduce fairway depth and create operational uncertainty for freight navigation. The activation of the extreme-event monitoring programme at the reference gauges Barby and Schöna in both 2025 and 2026 demonstrates the continuing relevance of prolonged low-flow conditions on the Elbe.

Overall, the comparison shows that the impact of low water cannot be expressed by a single hydrological indicator. On all three waterways, reduced water availability can limit vessel draught and transport capacity, but the resulting operational effects depend on river morphology, fairway conditions, infrastructure, and the spatial distribution of critical navigation sections. The Rhine is characterised primarily by substantial capacity reductions during severe low-water periods, the Danube by strong spatial variability and critical

bottlenecks along an extensive international waterway, and the Elbe by a high dependence of navigation conditions on natural hydrological variability.

These differences indicate that effective management of low-water conditions requires waterway-specific approaches. Continuous hydrological monitoring, reliable fairway information, timely communication of navigation restrictions, and adaptive vessel loading are essential measures for maintaining the reliability and safety of inland waterway transport. At the European level, increasing hydrological variability also strengthens the need to improve the resilience of inland navigation and to incorporate low-water scenarios into transport and logistics planning.

Indicator	Rhine	Danube	Elbe
Main low-water reference	Equivalent Water Level (EWL)	Low Navigable Water Level (LNWL)	Gauge/discharge reference thresholds
Hydrological characteristic	Free-flowing critical sections	High spatial variability	Strong dependence on natural discharge
Main operational effect	Draught and loading restriction	Draught restriction and local interruptions	Reduced fairway depth and reliability
Main logistical consequence	Reduced transport capacity	Lower capacity and disruption at bottlenecks	Reduced predictability of freight transport
Navigation continuity	Generally maintained with reduced loading	May be locally interrupted	Strongly dependent on hydrological conditions
Key low-water issue	Capacity limitation	Spatially distributed bottlenecks	Availability of sufficient fairway depth

Table 1 – Comparative Assessment of Low-Water Impacts on Selected European Inland Waterways
Source: author's own processing

Discussion

The comparative assessment of the Rhine, Danube and Elbe demonstrates that low-water conditions represent a common operational challenge for European inland waterway transport, although their consequences differ considerably between individual waterways. The results indicate that the severity of low-water impacts is determined not only by the hydrological situation itself, but also by the characteristics of the fairway, the location of critical sections, available navigable depth, waterway infrastructure and the ability of transport operators to adapt vessel loading and voyage planning to changing navigation conditions.

A common mechanism can be identified across all three waterways. A reduction in water level may result in a decrease in available navigable depth, which subsequently limits the permissible draught of vessels. For freight vessels, draught restrictions are directly associated with reduced cargo loading and therefore with lower utilisation of available carrying capacity. From a transport perspective, this relationship represents one of the most important consequences of prolonged low-water periods because the same volume of cargo

may require additional vessel movements, alternative transport arrangements or temporary redistribution to other transport modes.

However, the comparative results also demonstrate that the operational consequences are not identical. On the Rhine, navigation can generally be maintained during low-water periods, while reduced available depth primarily affects vessel loading and transport capacity. On the Danube, the spatial variability of navigation conditions and the occurrence of critical bottlenecks may result in more pronounced local restrictions and, under particularly unfavourable conditions, temporary interruptions. The Elbe shows a strong dependence on natural hydrological conditions, which may significantly influence the availability and reliability of sufficient fairway depth. These differences confirm that the impact of low water cannot be evaluated exclusively through water-level values without considering the specific characteristics of the individual waterway.

From a logistical perspective, low-water periods therefore influence not only vessel operations but also the reliability of the entire transport chain. Reduced carrying capacity can increase the number of vessel movements required to transport the same cargo volume, complicate transport scheduling and reduce the predictability of delivery times. These effects are particularly relevant for logistics systems in which inland waterway transport forms an integral part of multimodal transport chains. The ability to anticipate hydrological restrictions and incorporate them into transport planning is therefore becoming increasingly important for maintaining the competitiveness and reliability of inland navigation.

The safety dimension is equally important. Reduced navigable depth decreases the operational margin between vessel draught and the riverbed and consequently increases the importance of maintaining adequate under-keel clearance. Safe navigation under restricted depth conditions requires continuous assessment of available water depth, vessel loading, draught and local fairway conditions. This places increased demands on voyage planning, vessel handling and decision-making by boatmasters and other crew members. The European competence framework for inland navigation also reflects the importance of these abilities, including the assessment of water depth, loaded vessel draught and under-keel clearance within the competencies required for safe vessel operation.

The findings therefore indicate that effective management of low-water conditions requires an integrated approach combining hydrological monitoring, reliable information on fairway conditions, appropriate vessel loading strategies and qualified operational decision-making. Improving the availability and timely distribution of information on water levels, navigable depths and expected hydrological developments can support both transport planning and navigation safety.

At the same time, the results of the study should be interpreted with regard to the methodological limitations of a comparative assessment. The Rhine, Danube and Elbe use different hydrological and navigation reference systems, and absolute gauge values cannot therefore be directly compared without considering local reference levels and fairway characteristics. Future research should consequently focus on harmonised indicators, such as the number of days below defined navigation reference levels, duration of low-water periods, changes in permissible draught and corresponding reductions in vessel carrying capacity.

Such an approach could provide a more quantitative basis for assessing the resilience of European inland waterways to increasingly variable hydrological conditions.

Conclusion

The aim of this study was to assess the impact of low water levels on selected European inland waterways and to identify their operational, logistical and safety-related consequences. The analysis confirmed that low-water conditions represent an important limiting factor for inland waterway transport, primarily through the relationship between available navigable depth, permissible vessel draught and the utilisation of vessel carrying capacity.

The comparative assessment of the Rhine, Danube and Elbe demonstrated that the consequences of low-water periods differ according to the hydrological characteristics, fairway conditions and infrastructure of individual waterways. Despite these differences, a common operational mechanism can be identified. Reduced navigable depth may require vessels to operate at a lower draught, which consequently limits cargo loading and reduces available transport capacity. Prolonged low-water periods can therefore affect not only individual vessel operations but also transport reliability, voyage planning and the continuity of logistics chains.

The results also confirm that low-water conditions have an important safety dimension. Restricted navigable depth increases the importance of maintaining sufficient under-keel clearance and requires continuous assessment of water depth, vessel draught and local fairway conditions. Effective navigation under such conditions therefore depends not only on the technical parameters of the vessel and waterway but also on appropriate voyage planning, timely access to navigation information and competent decision-making by vessel crews. These requirements correspond with the European competence framework, which includes the assessment of water depth, loaded vessel draught and under-keel clearance among the elements relevant to safe vessel operation.

Future development of resilient inland waterway transport should therefore focus on improved hydrological forecasting, reliable and timely information on navigable conditions, effective management of critical fairway sections and the integration of low-water scenarios into operational and logistics planning. Further research should also focus on the development of harmonised indicators enabling quantitative comparison of low-water impacts across European inland waterways. Such an approach could contribute to more effective adaptation of inland navigation to increasingly variable hydrological conditions while supporting the reliability, competitiveness and safety of European inland waterway transport.

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