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CLIMATE IMPACT ON WATER DEPTH AS KEY FACTOR DETERMINING NAVIGABILITY OF THE INLAND WATERWAY

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Purpose: The navigability of inland waterways is critically dependent on maintaining sufficient water depth, which directly determines vessel loading capacity and transport costs. Increasingly frequent and severe climatic variability threatens the reliability of guaranteed depths on key European rivers. This study investigates the relationship between weather conditions and the number of days with reduced navigable depth. The central hypothesis is that climate-related anomalies significantly influence waterway depths and contribute to an upward trend in the number of days during which minimum guaranteed depths are not maintained within the navigation season.
Design/methodology/approach: The analysis focuses on the Rhine and Danube. Data from the Central Commission for Navigation on the Rhine were used, covering the period 2015-2023. The dataset includes the number of days in which required depths were not achieved at selected water gauges, including critical bottleneck locations. To test the research hypothesis, repeated-measures analysis of variance using Friedman ranks was applied. Where incomplete datasets were identified, regression imputation was used to ensure robustness.
Findings: Results confirm a significant impact of weather anomalies on the frequency of days with insufficient navigable depths along both rivers. For the Rhine, a statistically significant upward trend was identified, indicating a growing number of days with depths below guaranteed thresholds. In contrast, no significant upward trend was observed on the Danube, although depth deficiencies remain an operational challenge. The study further demonstrates that reduced guaranteed depths directly constrain inland waterway transport activity and intensification.
Research limitations/implications: The main limitation relates to data gaps in the lower Danube segment, addressed through imputation methods. Despite this, findings provide robust evidence of climate-induced disruptions to navigability. The results highlight the need for waterway authorities to adapt infrastructure and management strategies to ensure reliability under changing climatic conditions.
Originality/value: This article offers original empirical evidence of the climate–navigability nexus in European inland waterways. By quantifying the link between extreme weather events and guaranteed depths, it provides valuable insights for policymakers, river commissions, and infrastructure managers. The findings serve as both a warning and a foundation for future research, while supporting the case for modernisation of waterways and the elimination of bottlenecks to safeguard sustainable inland transport.

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Keywords: climate change, inland waterway transport, guaranteed depth of the waterway, barge loading factor.
Category of the paper: Research paper.

1. Introduction

The changes in the role of inland waterway transport in the transport system currently observed in Europe are not in line with the intermodal shift proposed in the White Paper on Transport and the 'Strategy for sustainable and intelligent mobility – European transport on the road to the future' (Fig. 1). In the EU-27 countries, between 2015 and 2023, transport performance in this transport mode decreased from 145.7 billion tkm to 116.4 billion tkm, and the share of this branch in the transport system fell from 6.9% to 5.1% in 2022 and 5,0% in 2023 (Eurostat, 2025a, 2025b). This was the lowest share since 2005.

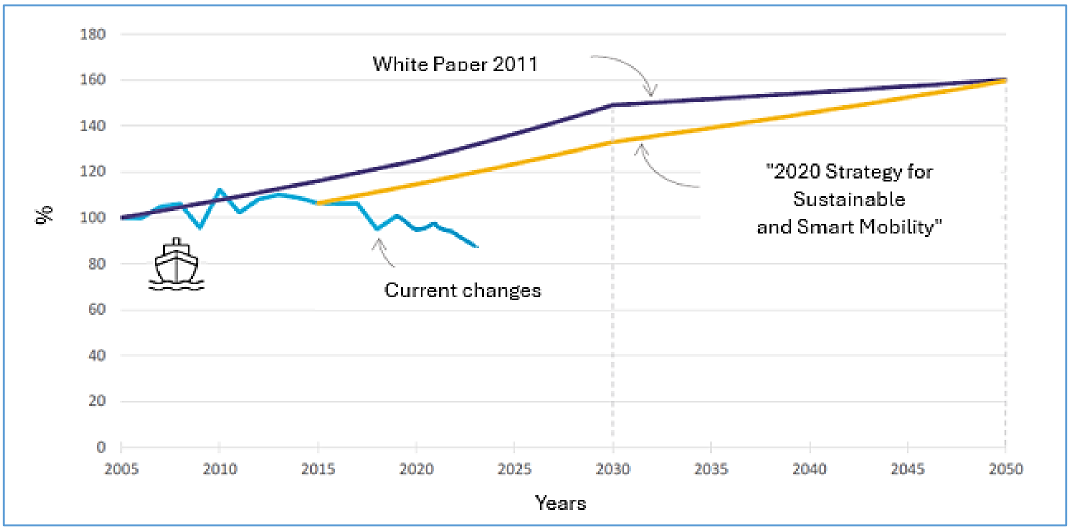

Figure 1. Comparison of inland waterway transport targets with actual transport performance (2005 = 100).

Source: Europäischer Rechnungshof 2023; Eurostat 2019, 2025b.

In order to reverse this unfavourable trend, it is necessary, among other things, to increase or at least maintain the existing capacity of inland waterways. The basic parameter determining the capacity of a waterway is its navigable depth[1] . The depth determines the size of the vessels

[1] Navigable depth in inland navigation is defined as:
- the minimum transit depth, i.e. the minimum depth of a waterway on a specific waterway or section thereof during the navigation season,
- guaranteed depth, i.e. the minimum transit depth with a specified percentage guarantee of its maintenance (for freely flowing European rivers, the degree of guarantee is 85-95%),
- maximum depth, i.e. the greatest depth on a specific waterway at which navigation can still be carried out due to limited clearance under bridges,
- average navigable depth, meaning the average draught of a vessel during the navigation season plus the required safety margin (Kulczyk, Winter, 2003).

that can be operated and the permissible draught of a ship. It is therefore a factor that directly affects the efficiency of inland waterway transport and the profitability of shipping operations (Stanisławczyk, 2005). The depth of the fairway determines the loading level of barges and, consequently, the unit transport costs (Van Dorsser, 2015; Vinke et al., 2022). The significant impact of the depth of the fairway, and consequently the draught of the barge, on the efficiency of inland navigation results from the slower increase in fuel consumption costs than the benefits associated with the increase in load capacity (Kulczyk, Winter, 2003). An increase in draught of 1 cm, for example in the case of a motor barge with a tonnage of 2,350 tonnes and dimensions L = 85, B = 11.45, T = 2.64, means an increase in the load on board by an average of 90 tonnes (Meetbrief voor Binnenvaartuigen, 2001). A reduction in the number of days with low water levels therefore has specific financial implications (Christodoulou, Christidis, Bisselink, 2020).

There is still a trend towards an increase in the average size of ships. The operating costs of large tonnage vessels are significantly higher than those of smaller ships. Therefore, the use of this type of vessel is economically justified in conditions of significant draught (VBD, 2004).

The need to maintain adequate fairway depths also stems from the AGN Agreement (European Agreement on Main Inland Waterways of International Importance) signed in 1996. According to the agreement, free navigation on inland waterways of international importance should be ensured 365 days a year, except in regions where severe climatic conditions prevent effective icebreaking operations during the winter. Interruptions to the navigation period due to low water levels are prohibited. At all times, the permissible draught shall not be less than 1.2 m, and for at least 240 days a year the draught shall be maintained at the level recommended for the waterway in question (United Nations, 1997).

The observed weather anomalies are a factor disrupting the maintenance of the required waterway depths. It can be assumed that these problems even affect waterways considered to be the main axes of the European inland waterway system, such as the Rhine and Danube. The study therefore aims to demonstrate the relationship between weather conditions and the number of days on which guaranteed depths are not maintained. The hypothesis is that weather conditions are the cause of the upward trend in the number of days on which guaranteed depths are not maintained during the navigation period.

2. Ship Draft and Hydrological Conditions as Factors Limiting Inland Waterway Transport

The loading level of barges is a function of their draught. Even ships currently in use that are considered small, i.e. vessels with a load capacity of up to 1500 tonnes (such as the Johann Welker and Europaschiff types), have a draught of between 2.5 m and 2.70 m when fully loaded (Nakoinz, 2010; VBD, 2004). On the Rhine, GMS-110 motor barges with a full load (approx.

3000 tonnes) have a draught of 3.5 m, and pushed convoys (11,000 tonnes) have a draught of 4.0 m (Beuthe et al., 2013). This means that the navigable depth of the waterway must be correspondingly higher. The navigable depth is determined by the draught and a specified safety margin. For the Rhine waterway, the safety margin is set at a minimum of 32 cm (CCNR, 2024). For the Danube, the safety margin is assumed to be between 20 and 40 cm (Meinel, 2024). However, studies show that due to the increase in water resistance during movement, this margin should be at least 1.0 m, or even 1.5 m, for a draught of 2.5 m (Kulczk, Winter, 2003).

Extreme droughts that have hit Europe have limited the availability of cargo space on ships operating even on the Rhine. According to measurements taken at the Iffezheim lock in Germany, the average loading level of ships for dry cargo transport in 2022 ranged from 60.6% in February to 31.3% in August (CCNR, 2023c). Also in 2023, low water levels on the Rhine meant that ships had to operate at a loading rate of only 40-70%, depending on their size (Tagesschau, 2023). Shipowners agree to operate their fleets at lower load factors, as keeping many vessels 'in limbo' would entail too great a reduction in revenue in relation to fixed costs (CCNR, 2023a).

Similarly, on the Danube, the unfavourable hydrological situation in 2022, caused by exceptionally high temperatures and lack of rainfall, made navigation impossible, with the maximum draught of vessels at 2.5-2.7 m. On the Danube in July 2022, barges in pushed convoys were operated at an average load of 1,150 tonnes (upstream) and 1200 tonnes (downstream), while 110-metre-long motor barges were operating at loads ranging from 950 tonnes to 1100 tonnes. However, motor barges with a length of 135 m were not used for transport purposes due to insufficient transit depths (DC, 2023).

The limited depth of the waterway due to drought necessitates the construction of much lighter vessels with a shallower draught. An example of this type of solution is a gas tanker (110 m x 12.5 m) built in 2021 and operated by the shipping company HGK Shipping (Cologne). This ship can be used even at extremely low water levels (Podgórski, 2021). In 2023, the shipowner introduced two more modern chemical tankers, Courage and Curiosity (93 m x 10.5 m), which can be operated at a draught of 1.0 m while maintaining the appropriate manoeuvrability and stability requirements (HGK, 2023).

Ships designed for shallow waters have significantly lower efficiency compared to traditional vessels. It is therefore unlikely that this type of vessel will constitute a significant part of the overall transport capacity of this branch of transport. Research shows that the large-scale construction of shallow-draught vessels would only be justified if low water levels occurred during 60-80% of the navigation period (Van Dorsser, 2015).

Therefore, despite the observed low water levels, the general hypothesis of a trend towards a reduction in the size of inland waterway vessels is not confirmed. In 2023, the average deadweight tonnage in the tanker group was 2510 tonnes and in the dry cargo vessel group was 1447 tonnes. For comparison, in 2012, the average deadweight tonnage of these vessels was

1919 tonnes and 1296 tonnes, respectively. In the Rhine basin countries, no vessels with a deadweight tonnage of up to 1000 tonnes for the transport of liquid cargo have been built since 2020. There is a greater tendency to build new vessels with larger tonnage. The average deadweight of new tankers in 2023 was 4022 tonnes, compared to 2868 tonnes in 2022. In turn, the average tonnage of newly built dry cargo ships in 2023 was 2664 tonnes, compared to 2499 tonnes in 2022 (CCNR, 2024). The increase in the share of ships with greater draught in the overall fleet observed over the last few decades has therefore made water transport highly cost-effective (Vinke et al., 2022). The operation of large vessels allows the mass transport advantage of this mode of transport to be maintained, i.e. the ability to move a large quantity of cargo in a single transport cycle. With a high share of fixed costs in this mode of transport, the ability to move a larger cargo weight consequently means a reduction in unit transport costs. Fixed costs in this branch of transport account for 60 to 65% (Niedzielski et al., 2021; CCNR, 2023b).

Problems with maintaining the required depths mean an increase in unit transport costs and are also a factor disrupting the continuity and reliability of transport services (transport service reliability). As a result, the confidence of cargo managers and freight forwarders in inland waterway transport as a reliable supply chain partner is reduced and the risk of customers withdrawing from transport contracts increases. For example, in Belgium in 2023, the decline in demand for inland waterway transport led to more than 275 shipping companies filing for bankruptcy (Stefaniak, 2023).

Waterway depths are the result of investments and expenditure on maintenance. While investment expenditure covers expenditure on new projects and the modernisation of waterways, maintenance expenditure is largely related to dredging. It is therefore crucial for maintaining guaranteed navigable channel depths on existing waterways. However, these expenditures are not currently eligible for co-financing under the Connecting Europe Facility II (CEF II) programme. Therefore, these expenditures, both for waterways included in the core network and the comprehensive TEN, are currently covered by the budgets of individual countries (CCNR, 2024).

Another important determinant of existing depths is the volume of water flow in rivers, which is a result of precipitation levels. Lack of precipitation and accompanying droughts cause a reduction in average flow levels (Christodoulou, Christidis, Bisselink, 2020). In 2022, flows below the reference period average (1991-2020) were recorded in 63% of rivers. In contrast, 26% of rivers had exceptionally low flows and 20% had particularly low flows. The problem of record low flows in 2022 particularly affected rivers in the Danube, Rhine, Meuse and Loire basins (ESOTC, 2022). It can even be assumed that the frequency and scale of disruptions associated with low water levels will increase in the future (Scholten, Rothstein 2016; Van Dorsser, 2015).

Due to rapid climate change, greater problems can be expected in maintaining the required navigable depths, which may even result in the inability to transport cargo by inland waterways (De Jong, 2020). Maintaining adequate waterway depths is therefore essential for maintaining the efficiency of the inland waterway transport sector and increasing its role in the transport system.

3. Data and method

The actual depth of the fairway does not correspond to the water level readings at the water gauge station. Therefore, the following are used to determine the navigable depth of a waterway:

- for the Rhine waterway - an indicator referred to as the equivalent water level (WWL),
- for the Danube waterway - an indicator referred to as the low navigable water level (LNWL).

There is a relationship which shows that if the water level on the water gauge is consistent with the WWL or LNWL, the minimum guaranteed depth of the fairway for a given section is maintained (CNNR, 2024). Therefore, if on a given day the depth on the water gauge is lower than that specified for WWL (Rhine) and LNWL (Danube), this means that the guaranteed depth on the route is not maintained.

The number of days with a depth lower than the guaranteed depth was determined for 11 selected measuring stations on the Rhine waterway and 11 stations on the Danube waterway. The selection of measuring stations was based on data availability. Four measuring stations that are of key importance for navigation on these waterways were considered. On the Rhine, these stations are located in Kaub and Ruhrort, and on the Danube in Wildungsmauer and Hofkirchen (Christodoulou, Christidis, Bisselink, 2020).

The study used data from CCNR annual reports collected for the period 2015-2023. During data collection, a problem arose with incomplete data for measurements on the lower section of the Danube. The missing data concerned measurements at the Lom and Silistra water gauging stations (2015) and at the Calafat and Calarasi stations (2023). This problem was resolved by replacing the missing data with a specific numerical value. For this purpose, regression imputation was used (Piasecki, 2014; Pokropek, 2018). According to this method, it was assumed that there is a relationship between the water levels at the gauges for which the data gap problem occurred and the water levels at the neighbouring measuring station. The distribution of days on which depths lower than those guaranteed for the Rhine waterway were recorded is presented in Table 1, and for the Danube waterway in Table 2.

The study used analysis of variance of repeated measurements for Friedman ranks, i.e. Friedman repeated measures analysis of variance by ranks (Black, 2010). The method for repeated measurements was chosen because the data for the selected water gauges were recorded at repeated intervals (2015-2023). The use of a rank-based test is a result of the failure to meet the assumption of normal distribution of the variable in all compared periods. In the case of the Rhine, the Shapiro-Wilk test did not confirm the normality of the variable distribution in 2018, 2019 and 2022, and in the case of the Danube - in 2017. In the years mentioned, the test statistic (left-tailed test) was lower than the critical value W^{*}= 0.850 for $n = 11$ the significance level of $\propto = 0.05$. The conclusion was therefore based on the median value determined from the distribution of the number of days on which the guaranteed depths were not maintained on the Rhine and Danube waterways.

Table 1.
Number of days below the equivalent water level (EWL) for the Rhine gauge stations in years 2015-2023

Water gauge	2015	2016	2017	2018	2019	2020	2021	2022	2023
Basel (upper section)	8	7	24	48	0	0	0	7	4
Maxau (upper section)	30	27	28	80	0	0	6	23	8
Oestrich (middle section)	23	18	27	78	0	0	4	22	7
Kaub (upper section)	29	19	28	107	0	0	10	41	4
Cologne (lower section)	37	26	23	121	0	11	9	52	11
Duisburg-Ruhrort (lower section)	39	35	25	128	3	14	13	60	9
Emmerich (lower section)	46	36	25	134	4	25	27	65	9
Lobith (lower section)	34	29	25	131	4	20	16	64	11
Nijmegen (lower section)	31	29	24	136	3	17	14	62	10
Ijsselkop (lower section)	40	34	25	136	5	30	22	65	8
Tiel (lower section)	27	22	22	131	0	13	0	62	6

Source: CCNR, 2023a; 2024.

Table 2.
Number of days below the low navigable water level (NNWL) for the Danube gauge stations in years 2015-2023

Water gauge	2015	2016	2017	2018	2019	2020	2021	2022	2023
Pfelling (upper section)	106	22	38	148	47	84	36	71	79
Hofkirchen (upper section)	92	6	18	126	13	50	21	52	52
Kienstock (upper section)	35	12	24	55	7	5	27	6	21
Wildungsmauer (upper section)	54	23	37	89	27	31	47	36	30
Devin (upper section)	66	19	32	80	12	4	20	22	29
Budapest (middle section)	60	13	19	85	12	1	17	22	25
Bezdan (middle section)	66	19	16	97	31	0	38	71	36
Calafat (lower section)	118	36	92	114	100	53	53	127	82*
Calarasi (lower section)	75	24	32	82	89	23	47	119	57*
Lom (lower section)	62*	17	44	74	54	8	49	108	37
Silistra (lower section)	50*	18	22	77	75	25	53	44	43

* missing data estimated using regression imputation method.

Source: CCNR, 2023a; 2024.

When verifying the research hypotheses, they were transformed into a statistical hypothesis, giving it a formal (quantitative) structure (Black, 2010). In accordance with the most used concept of statistical hypothesis testing, the Neyman-Pearson approach was used, consisting in formulating null hypotheses and corresponding alternative hypotheses (Burnewicz, 2021). Two null hypotheses were formulated:

- the median number of days with a depth lower than the guaranteed depth does not change depending on weather conditions,
- the median distribution of days on which the waterway depth is lower than the guaranteed depth does not show an upward trend.

The alternative hypotheses are the opposite of the null hypotheses and were formulated as follows:

- the median number of days with reduced guaranteed depth changes in relation to the impact of weather conditions;
- the median number of days with reduced guaranteed depth shows an upward trend.

Among the proposed test statistics within the Friedman ANOVA method, the $T2$ *Iman-Davenport statistic* was used to examine the relationship between the weather factor and the number of days with reduced navigational depth in the compared periods. This statistic considers the correction for tied ranks and is therefore more recommended. To verify the null hypothesis of no increasing trend in the number of days on which depths were not maintained on the Rhine and Danube waterways, a *Page* test for trend was performed. The conclusions of this test were based on the statistic Z. The use of this statistic is reliable when the numbers n and $k$are sufficiently large ($k > 8$, regardless of the value of n) (Zaiontz, 2025). In this case, this condition is met, as $k = 9$, and $n = 11$.

As the base significant value was adopted the valueof $\propto = 0.05$. To tighten the evaluation criteria, the study was also conducted for a reduced level of $\propto = 0.001$, at which it is more difficult to reject the null hypotheses.

4. Results and discussion

The median values for the number of days on which depths lower than the guaranteed depth were recorded in 2015-2023 at selected water gauges on the Rhine and Danube waterways are shown in Fig. 2 and 3. The varying median values suggest that weather conditions influence the number of days with depths lower than guaranteed on these waterways.

As shown in Table 3, the test statistics $T2$ for the null hypothesis that the median number of days with depth below the guaranteed level does not vary depending on weather factors are 79.25 for the Rhine waterway and 15.25 for the Danube waterway. These statistics are significantly higher than the critical value determined from the F-Snedecor distribution table for 8/80 degrees of freedom and $\propto = 0.05$ (2.06), and even higher than the critical value for $\propto = 0.001$ (3.70). Thus, even for a more stringent level of α, the null hypothesis must be rejected and the significance of the weather factor's impact on the number of days on which the guaranteed depths on the Rhine and Danube waterways were not maintained must be accepted.

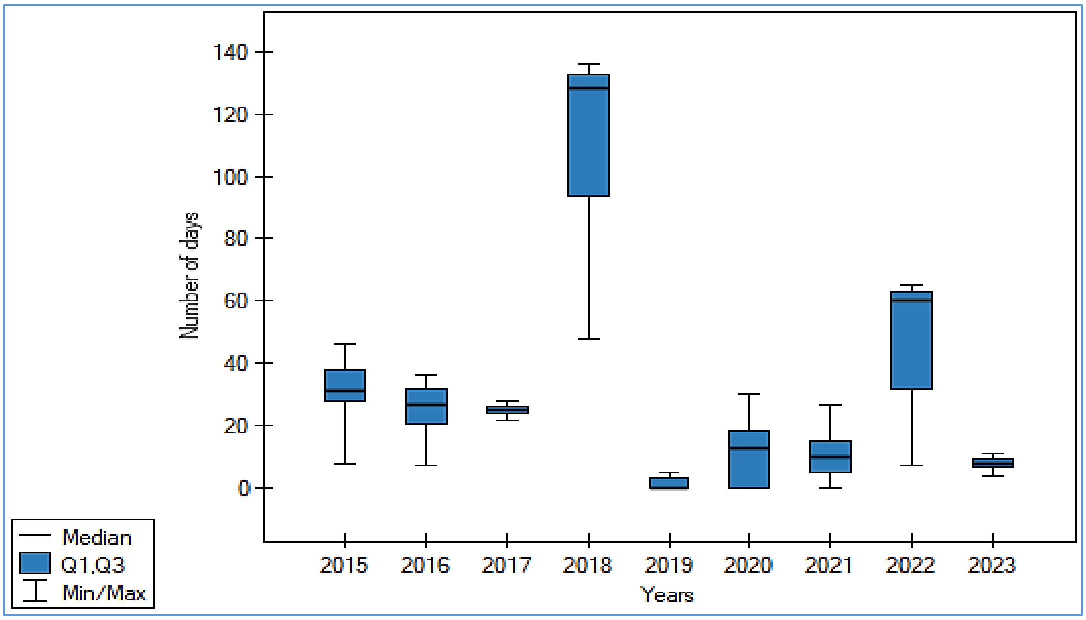

Figure 2. Median number of days with depth below the guaranteed level on the Rhine waterway in 2015-2023.

Source: own ellaboration using PQStat software.

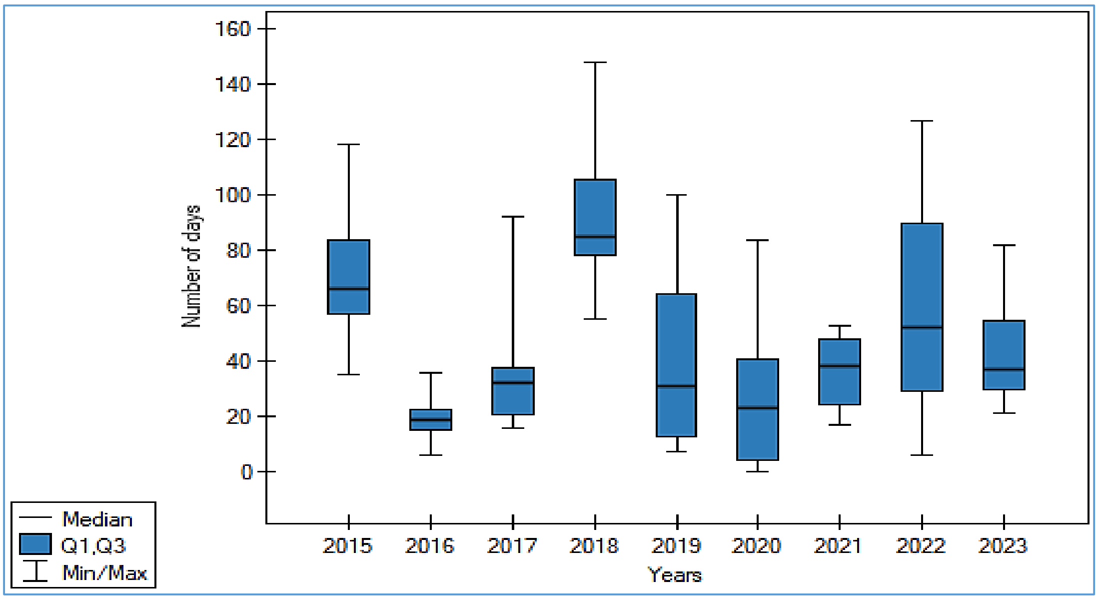

Figure 3. Median number of days with depth lower than guaranteed on the Danube waterway in in 2015-2023.

Source: own ellaboration using PQStat software.

Table 3.
Friedman ANOVA results

Specification	Rhine	Danube
Number of unspecified	0	0
Number of missing data	0	0
Significance level	0.05	0.05
$T2$ statistic Iman-Davenport	79.255583	15.963467
Degrees of freedom	8 / 80	8/80
p-value	<0.000001	<0.000001
Critical Values for T2 Statistic (∝ = 0.05)	2.06	

Source: own ellaboration using PQStat software.

In the case of the Rhine River, the study also confirms a statistically significant upward trend in the number of days with depths below the guaranteed depth. As shown in Table 4, the test statistic for the measurements taken on the Rhine waterway is 3.65. This value is even higher than the critical value for ∝ = 0.001 (3.09). However, there is no basis for claiming that on the Danube, the number of days on which the depths on the shipping route fall below the guaranteed depth shows an upward trend. In this case, the test statistics are lower than the critical value.

Table 4.
Page test results for trend

Specification	Rhine	Danube
L statistic	2.218	2.454
Z statistic	3.652839	0.298481
One sided p-value	0.000259	0.382668
Critical Values for Z Statistic (∝ = 0.05)	1.65	
Critical Values for Z Statistic (∝ = 0.001)	3.09	

Source: own ellaboration using PQStat software.

The results obtained indicate that the problem of maintaining guaranteed depths is more pronounced on the Rhine than on the Danube. This is also confirmed by other studies on the impact of weather conditions on guaranteed depths at key points for maintaining navigation on these waterways. It is predicted that on the Rhine, both in the Ruhrort and Kaub measuring stations, the average number of days with low water levels will increase by the end of the century, with a slight increase in the Kaub area. In contrast, in areas critical for navigation on the Danube (Wildungsmauer and Hofkirchen), the number of days with low water levels is expected to decrease by the end of the century (Christodoulou, Christidis, Bisselink 2020).

Problems with maintaining the required guaranteed depths are directly related to the intensity of transport use of waterways. During the period under review, i.e. 2015-2023, traditional shipping (transport between Basel and the Dutch-German border) on the Rhine decreased from 185.7 million tonnes to 146.1 million tonnes. The volume of cargo transport on this main European inland waterway axis in 2023 was the lowest since the 1970s (CCNR, 2024). Between 2015 and 2023, a decline in transport was recorded on all sections of the Rhine waterway, with the largest declines in the middle (23.2%) and lower (22.3%) sections (BDB, 2025).

The Danube waterway is characterised by significantly lower transport intensity than the Rhine. On an annual basis, cargo transport on the entire navigable route from Kelheim (Germany) to the Black Sea via the Danube-Black Sea Canal and the Sulina Canal fluctuates between 34 and 40 million tonnes (CCNR, 2024). In recent years, a decline in transport on this waterway has been observed in the upper and middle sections. A different trend is observed in the lower section, especially in the Danube delta region. A significant increase in cargo transport in this region was recorded after 2022. Compared to 2020, freight transport on the lower section and in the Danube delta region increased by 4.8% in 2022 and by 41.8% in 2023 (Semyonovich Suvorov, 2024, p. 28). This is the result of the continuing good navigation conditions in this area and the increased use of this waterway for transport under the EU-Ukraine Solidarity Lanes system.

5. Summary, limitations and future research

The study provides compelling evidence that weather-related anomalies, particularly prolonged droughts, are a critical determinant of navigational depth on key European inland waterways such as the Rhine and Danube. The statistically significant increase in the number of days with insufficient depth on the Rhine confirms the growing vulnerability of inland waterway transport to climate variability. This directly affects the modal shift potential envisaged in EU transport policies and hampers the economic viability of larger, more efficient inland vessels.

The study was limited by gaps in hydrological data from several gauge stations, particularly on the lower Danube. While regression imputation was used to estimate missing values, this introduces potential biases and may not fully reflect complex local hydrodynamic conditions. Moreover, the analysis did not account for broader climatic indices (e.g. NAO, ENSO) or local interventions (e.g. dredging schedules), which could provide further explanatory power.

As for the future research the authors point out the following topics:

1. Climate Modelling Integration: Future studies should integrate regional climate model projections (RCMs) with hydrological and transport models to assess future navigability under various climate scenarios.
2. Cost-Benefit Analysis of Adaptation: A comprehensive economic assessment of adaptation strategies - such as riverbed stabilisation, dredging, and the design of low-draught vessels - is essential.
3. Fleet Modernisation Scenarios: Research should explore how expected changes in navigability affect fleet investment strategies and the technological transformation required for climate-resilient inland navigation.

4. Hydrological Forecasting and Risk Management: Advancements in real-time water level forecasting, especially under extreme climate events, would support better traffic planning and risk mitigation for freight operators.
5. Cross-modal Impact Assessment: The broader impacts on intermodal supply chains - especially modal shifts to rail or road in response to prolonged navigational limitations - should be quantified.
6. Institutional and Policy Frameworks: It is necessary to evaluate the effectiveness of current EU funding mechanisms and regulatory instruments in supporting the resilience and sustainability of inland waterways in the face of climate change.

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