ARTICLE IN PRESS

Transportation Research Part D xxx (xxxx) xxx

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

The impact of critical water levels on container inland waterway transport

Felipe Bedoya-Maya *, Peter Shobayo, Joris Beckers, Edwin van Hassel

University of Antwerp, Department of Transport and Regional Economics, Antwerp 2000, Belgium

ARTICLE INFO

Keywords:
Inland waterway transport
Climate change
Water levels
Resilience
Uncertainty

ABSTRACT

This paper disentangles the impact of critical water levels on container cargo transported along the Rhine River. It analyzes monthly throughput and all instances where navigability was constrained due to low or high water levels between 2000 and 2022, employing a time series econometric model. The study considers water level conditions at critical locations between economic centers while controlling for confounding effects. Our findings reveal an average monthly impact of -0.2% per day of disruption and -5.9% when the disruption remained for more than 24 days. Notably, vulnerability to critical conditions has doubled since 2018 and exhibits spatial variation. The most pronounced disturbances and their lagged effects are associated with localized low water level incidents. We show that enhancing the resilience of inland waterways to climate change is essential to avert potential losses in container throughput, estimated to range between 7% and 20% annual average by 2050.

1. Introduction

Inland waterway transport (IWT) can significantly contribute to the sustainable development of port-hinterland connections. Specifically, by utilizing barges that can transport the equivalent of 200 trucks on average, the external transport costs can be reduced (INE, 2016). IWT's minimal generation of accidents, noise, congestion, habitat damage, and emissions has spurred global policy agendas to encourage a shift toward a more sustainable freight transport market structure (Björk et al., 2023). Although rail transport incurs the lowest external costs in €/ton-km in Europe, IWT's external costs are about half those of road transport (European Commission, 2019; Kendra et al., 2023).

The development of IWT is also relevant in terms of regional integration in Europe. The EU's Trans-European Transport Network (TEN-T) has identified the Rhine-Alpine Corridor (RALP) as a vital regional corridor to establish an integrated, competitive, and sustainable transport network by 2030 (European Commission, 2017). The navigable RALP connects Belgium, the Netherlands, France, Germany, Luxembourg, and Switzerland. With approximately forty inland terminals handling over 500 million tons of cargo annually, the vast majority of Europe's freight IWT is conducted between countries within the RALP network (Eurostat, 2022).

To maximize its potential in reducing negative transport externalities and enhancing regional integration, the competitiveness of IWT hinges on maintaining navigable conditions and developing resilient responses to extreme weather events, which climate change is intensifying. Specifically, extremely low water conditions primarily reduce vessels' loading capacity, while critically high water levels can inflict significant damage on transport infrastructure (Michaelides et al., 2014). The repercussions of these critical episodes

* Corresponding author.
E-mail address: felipe.bedoyamaya@uantwerpen.be (F. Bedoya-Maya).

https://doi.org/10.1016/j.trd.2024.104190
Received 27 December 2023; Received in revised form 16 March 2024; Accepted 29 March 2024
1361-9209/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Please cite this article as: Felipe Bedoya-Maya et al., *Transportation Research Part D*, https://doi.org/10.1016/j.trd.2024.104190

include increased transport prices, higher energy consumption, and market losses, predominantly to road transport (CCNR, 2022b; Eurostat, 2023b).

From 2007 to 2021, a negative trend was observed in Europe's freight IWT, coinciding with an increase in road transport market share (Eurostat, 2023b). This trend intensified following the significant market loss after the dry summer of 2018. While the occurrence of low and high water level conditions is not new in the RALP, their impact on IWT has grown. In 2018, the number of days with water levels below the minimum navigable threshold of 78 cm at Kaub, Germany—a critical point for much of the RALP network—reached 107 days. This figure is notably lower compared to earlier extreme years, such as 1949 (173 days), 1921 (156 days), or 1971 (146 days). However, traffic along the Rhine during 2018 experienced an unprecedented decline in recent history (-11.9%), almost double that of 1971 (-6.2%) (CCNR, 2021). Similar future events pose a threat to the supply chains serving Europe (European IWT Platform, 2022).

The majority of empirical literature available for understanding the phenomenon of critical water levels focuses on simulations and their potential impacts on total throughput, without differentiating between types of cargo. Michaelides et al. (2014) documented the effects of climate and hydrological change on navigation in the Middle Rhine, using the simulation model of total IWT conducted by Schweighofer et al. (2012). The results showed no significant effects of low water levels on IWT between 2021 and 2050 compared to the control period of 1961-1990. For the end of the twenty-first century (2071-2100), the simulation suggested that the trend towards drier summers and wetter winters would become more significant in determining adverse effects. Additionally, the authors noted that the propensity for ice formation on the Rhine would likely decrease throughout the century, which is closely related to water levels.

Koetse and Rietveld (2009) conducted a review of the economic impact of critical water levels on the total throughput of IWT and concluded that longer and more frequent periods of low water levels would likely occur, influencing transport prices per ton. In Canada, Millerd (2005) projected that the average increase in operational costs for the Great Lakes River system due to climate change could rise between 3% and 14% by 2030, depending on the industrial sector, and between 6% and 22% by 2050. Olsen et al. (2005) analyzed the Middle Mississippi River between 1933 and 2002, finding that losses attributable to low water level conditions averaged $77 million annually. In simulating scenarios for 2100, they reported high uncertainty with potential annual average losses ranging from $10 to $118 million. The authors also documented average annual losses of $12 million due to high water levels for the period 1933-2002 and predicted potential losses ranging from $1.5 to $41 million for 2100.

In Europe, Jonkeren et al. (2007) estimated the welfare loss due to low water levels in Kaub between 1986 and 2004 at €28 million, with a peak of €91 million during the dry summer of 2003. Cost comparisons should be approached with caution, taking into account the monetary value of each year mentioned in the publications. Bruinsma et al. (2012) examined the Rotterdam-Basel route and employed an econometric regression to illustrate the interaction between water levels, transport costs, and prices by vessel type. They found that the advantages of using larger ships become disadvantageous under low water level conditions, leading to a significant increase in costs. Given that IWT on the Rhine operates in a competitive market, these cost changes are quickly reflected in transport prices. Additionally, UTP Erasmus (2020) surveyed stakeholders in Germany and the Netherlands to assess the financial impact of the prolonged low water levels in 2018. Remarkably, the total financial impact on Germany and the Netherlands was estimated at a loss of €2.7 billion, predominantly due to a decrease in production for German shippers (81%). By contrast, the total financial impact on the Netherlands was 11% of the total, mainly owing to a 9% increase in transport costs for shippers.

The related literature has discussed the influence of prolonged episodes of critically low water levels, the potential loss of market share, and an increase in the number of smaller vessels. Using the NODUS simulation model, Jonkeren et al. (2011) estimated that IWT in Europe could lose about 5.4% of the freight transported annually. For the same region, Jonkeren et al. (2014) reported a potential modal shift of 5-8% due to low water levels. These studies did not differentiate between types of cargo and vessels. An exception is the study by Vinke et al. (2022), which simulated bulk transport for the segment between Rotterdam and Duisburg during the disruption caused by low water levels in 2018. Their results indicated that the impact of low water levels varies between vessel types due to cascading effects on fleet composition, number of trips, congestion in seaports, and storage capacity at the destination. The only optimistic analysis is by Christodoulou et al. (2020), who considered fewer days with low water conditions at four locations on the Rhine and Danube rivers, followed by a potential economic benefit for IWT of €8 million annually.

Although previous studies have developed comprehensive simulations of the Rhine inland network and considered various scenarios regarding water conditions, a gap in the literature remains concerning the temporal and spatial patterns of the impact on container IWT. Specifically, there is limited knowledge about the number of days with critical conditions required to cause a significant decrease in IWT and the duration of such an effect after the disruption occurs. Furthermore, since previous studies on IWT have not differentiated according to cargo type, there is scant evidence concerning containerized cargo and how the impact of critical water levels may vary between locations along the inland network. The objective of this paper is to unravel these patterns, aiming to enhance our understanding of the phenomenon and inform resilience policymaking. Consequently, our primary research question is: What are the temporal and spatial patterns of the impact that critical water levels have on container IWT in the Rhine River?

Assessing the temporal and spatial patterns of the disruptive effect also enables us to explore the consequences of likely similar disruptions in the future. According to the literature reviewed, the occurrence and duration of critical episodes are expected to increase due to climate change (Deltares, 2023; KNMI, 2023; Koetse & Rietveld, 2009). Specifically, the incidence of critically low water levels in the RALP is likely influenced by the rise in global temperature and changes in atmospheric circulation (Jonkeren et al., 2011). A more pronounced change in temperature and atmospheric circulation is associated with drier and warmer summer conditions (Deltares, 2023). We consider a set of scenarios for 2050 to explore the subsequent question: What are the potential implications of anticipated climate change scenarios?

Hence, the contribution of this study to academic literature and resilience policymaking can be divided into three parts. First, the econometric approach quantifies the magnitude of the impact that critically low and high water levels have had on monthly container

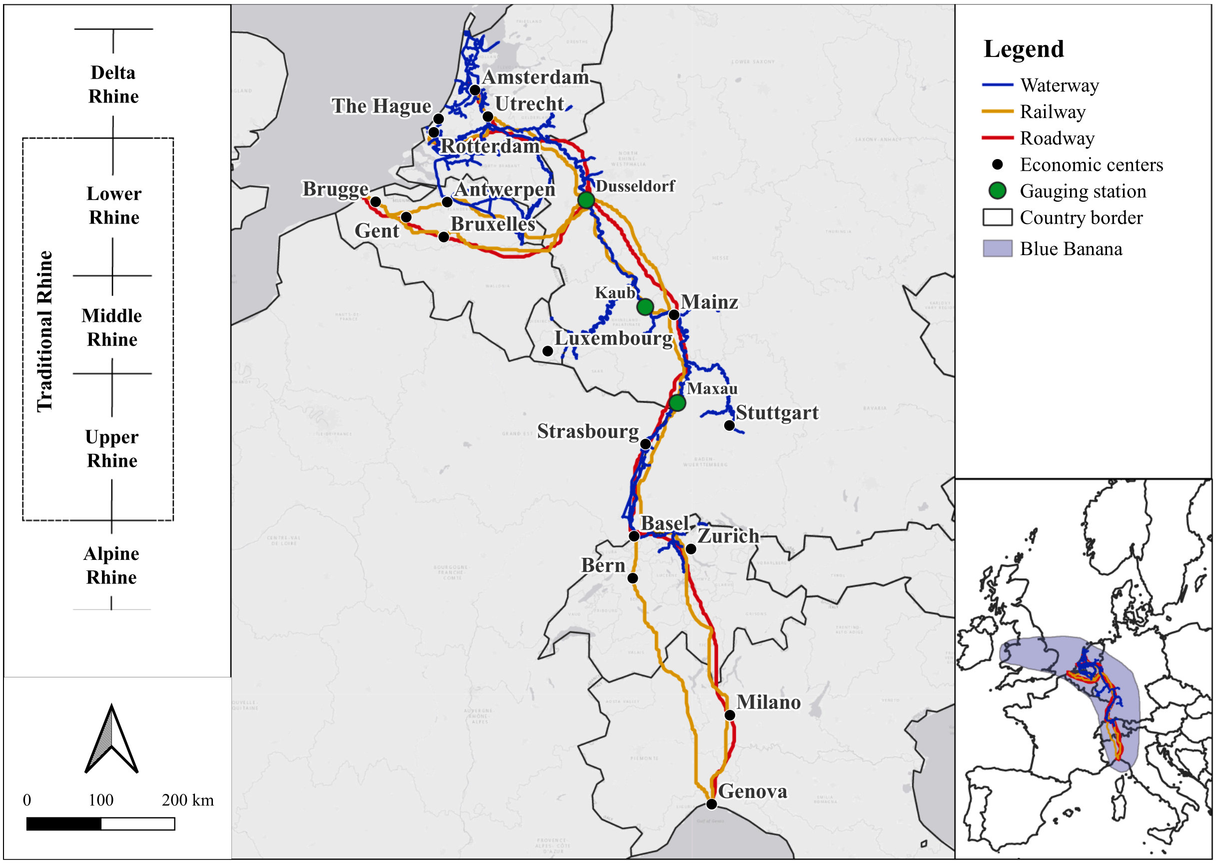


Figure 1. The Rhine-Alpine corridor. Source: Adaptation from Bedoya-Maya et al. (2023).

throughput from 2000 to 2022, and how this impact has evolved over the last five years (2018-2022). Second, it clarifies the temporal gap before and after a new critical episode causes a significant adverse effect on throughput. Third, the impact is measured at a more detailed spatial level by disaggregating the effects according to where the disruption occurs along the transport corridor. Specifically, the variability of water levels is assessed at nine critical locations between economic centers of the inland network. Based on these findings, resilience measures are discussed after predicting the potential average losses based on climate change scenarios for 2050.

The remainder of the paper is organized as follows: Section 2 presents the study area and reviews container IWT trends from 2000 to 2022. Section 3 explains the consolidated dataset, including the criteria for defining critical water level conditions. This section also explains the econometric approach and the climate change scenarios used for the predictive analysis. Section 4 presents the results, and Section 5 discusses their policy implications. Finally, Section 6 concludes the paper.

2. Empirical framework

The RALP is one of the busiest inland waterway transport corridors in the world, connecting the core seaports of the North Sea with northern Italy (see Figure 1). It links the main economic centers of the “Blue Banana” area, home to around 100 million inhabitants in cities and towns across Belgium, the Netherlands, Germany, Luxembourg, France, Switzerland, and Italy (Bedoya-Maya et al., 2023). Currently, most of the European cargo transported by waterways consists of commodities, such as fossil fuels, mining, and quarrying-related goods (Eurostat, 2022). However, containerized transport by IWT has spare capacity to offer a more sustainable market structure in the RALP (European Commission, 2017). In 2022, container transport performance reached 1.4 billion TEU-km, representing 9.8% of total IWT (Eurostat, 2023a).

The hydrological sources of the Rhine originate in the Alpine region, with its confluences enabling navigability to the Delta Rhine. Most cargo is transported along the so-called “Traditional Rhine,” which consists of the Lower, Middle, and Upper segments. It is along the Traditional Rhine that container IWT predominantly engages in competitive interplay with road and rail modalities to serve the hinterland, demonstrating a comparative advantage for extended distances due to economies of scale associated with transport efficiency (European Commission, 2017; Shobayo & van Hassel, 2019).

Within this framework, the navigability requirements based on water levels vary between stretches of the Rhine and can differentially affect transport flows within the network. Figure 1 illustrates three reference gauging stations. First, Dusseldorf in the Lower Rhine is notable for its proximity to the critical inland hub of Duisburg, the busiest inland port in the network. It also serves as a vital

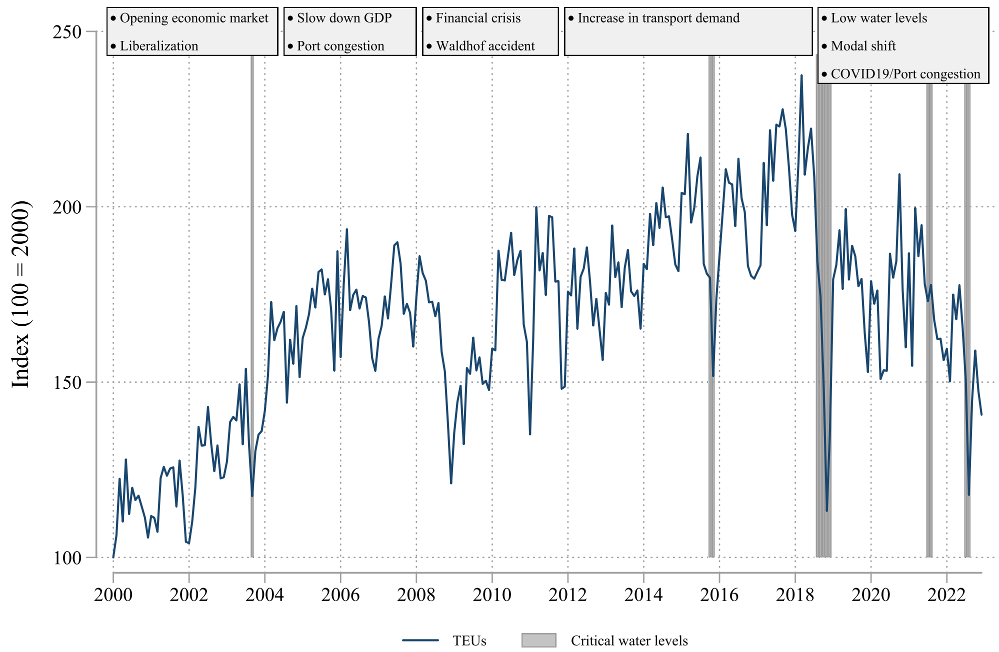


Figure 2. Time series of container IWT in the traditional Rhine. Note: Adaptation from Van Meir et al. (2022).

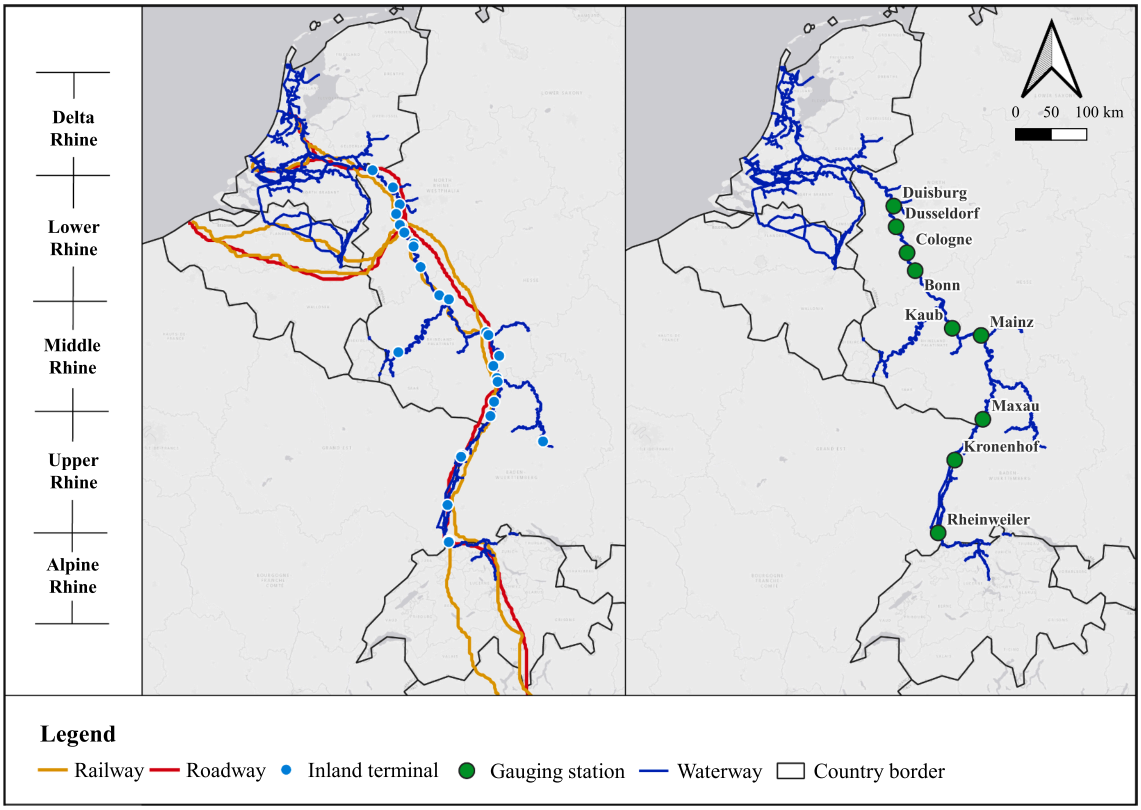
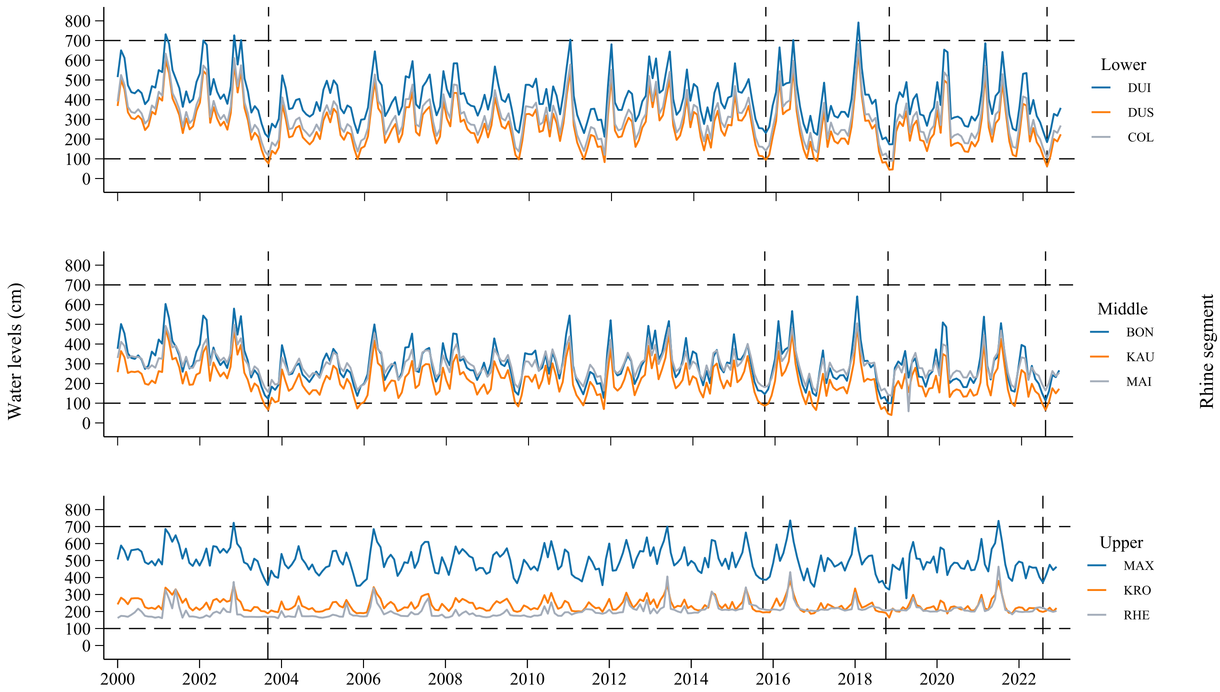


Figure 3. Locations for data collection



Legend

Duisburg (DUI), Dusseldorf (DUS), Cologne (COL), Bonn (BON), Kaub (KAU), Mainz (MAI), Maxau (MAX), Kronenhof (KRO), Rheinweile (RHE)

Figure 4. Time series of water levels and major critical episodes

interchange where road and rail routes provide alternatives to reach the deep seaports in Belgium and the Netherlands. Second, Kaub, located at the heart of the Rhine, plays a critical role; any navigable disruption here can create a bottleneck, affecting connections between the Delta and Lower Rhine (including the North Sea seaports) and the inland terminals in Switzerland, the Alsace region in France, and the Danube Canal. Finally, Maxau, situated at the border between Germany and France in the Upper Rhine and moving towards the corridor's last terminal in Basel (Switzerland), faces navigability limitations during extremely high water levels due to the presence of numerous bridges.

Figure 2 illustrates the trends of container IWT in the traditional Rhine. Since 2000, the combination of an open economic market, the liberalization of IWT, and increased container flow from Rotterdam and Antwerp resulted in an average monthly growth of 2.7% up until 2004 (Van Meir et al., 2022). However, the heatwave and lack of rainfall in 2003 led to low water levels and a 5.8% reduction in Rhine traffic compared to the previous year. From 2004 to 2008, container IWT experienced a growth of 0.3%, correlating with an economic slowdown in Germany and Switzerland (2006-2008) and high port congestion in Rotterdam and Antwerp (Van Meir et al., 2022). The financial crisis impacted global container transport in the subsequent two years. In 2011, the Waldhof accident on the Middle Rhine, involving a capsized chemical tanker near Kaub, caused a significant disruption in navigability.

From 2011 to 2018, a generally positive trend was observed, attributed to increased container flows in seaports. However, critically low water levels near Dusseldorf at the end of 2015 led to a 4.0% decrease in Rhine traffic compared to 2014 (CCNR, 2021). In 2018, after 107 days with critically low water levels at Kaub, the Rhine experienced its most significant year-over-year traffic decrease in recent decades (-11.9%). This event coincided with the largest market loss recorded since 2007 (-10.8%), primarily to road transport (Eurostat, 2023b). In 2020, container throughput returned to levels seen a decade earlier. Then, high water levels in Maxau at the end of 2021 were followed by a negative trend, exacerbated by the dry summer of 2022, which persists to the present day. These recent episodes of critical water level conditions can provide valuable insights into the temporal and spatial impact patterns. The next section outlines the consolidated dataset and econometric approach employed in this study to unravel these patterns.

3. Data and Methods

We compiled a dataset with monthly container throughput, measured in TEUs, from January 2000 to December 2022, as shown in Figure 2. The data, sourced from Destatis and CCNR, measures transport flows across all inland container terminals along the Lower, Middle, and Upper stretches of the Rhine (left panel of Figure 3). The average throughput is approximately 160 thousand TEUs per month, with a coefficient of variation of 17%. The number of containers transported reached a peak of 225 thousand TEUs in March 2018, just prior to the disruption caused by sustained low water levels.

Table 1
Parameters per location

Segment	Location	p05	p95	MNCD*	EWL*
Lower	Duisburg	227	682	280	233
	Düsseldorf	96	526	-	91
	Cologne	138	564	250	139
Middle	Bonn	142	536	-	142
	Kaub	82	405	190	77
	Mainz	173	440	-	171
Upper	Maxau	371	667	210	369
	Kronenhof	192	330	-	-
	Rheinweiler	165	317	-	-

Notes: Minimum navigation channel depth (MNCD).
Equivalent water level (EWL). * Obtained from CCNR (2022).

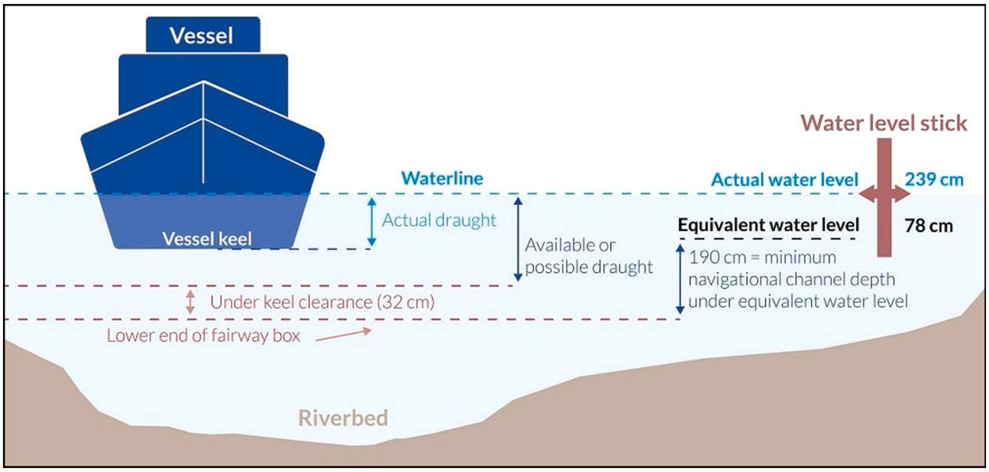


Figure 5. Equivalent water level and minimum navigational channel depth at Kaub Source: CCNR (2022).

To account for the influence of water level fluctuations on container flows, we collected daily water level data over the same timeframe (2000 - 2022) from RhineForecast.com. The dataset includes reports from nine critical locations evenly distributed across the Rhine segments, as shown in the right panel of Figure 3. For the Lower Rhine, we gathered water level data at Duisburg, Düsseldorf, and Cologne, significant for their industrial activity. In the Middle Rhine, the heart of the river, reports were collected at Bonn, Kaub, and Mainz. Finally, for the Upper Rhine, we gathered data at Maxau, Kronenhof, and Rheinweiler, providing insights into the conditions affecting the upper reaches of the waterway closer to France and Switzerland.

In Figure 4, we indicate the most significant disruptions to IWT over the past twenty years, focusing on instances where low water conditions coincided with substantial decreases in container flows via IWT, as shown in Figure 2 (i.e., 2003, 2015, 2018, and 2022). To denote low and high water level situations across locations, Figure 4 introduces two reference lines at one and seven meters of water depth. However, the thresholds at which water levels become insufficient for navigation are not universally applicable but depend on the morphological features of the river at each location. Therefore, we refer to navigability criteria from the existing literature by the CCNR (2022) to identify episodes with critical water levels along the Rhine.

Table 1 summarizes these critical navigational parameters, detailing the Minimum Navigational Channel Depth (MNCD) alongside the Equivalent Water Level benchmarks (EWL). The EWL represents a threshold below which, on a century-long average, water levels did not fall for more than 20 ice-free days annually. It serves as a low-water mark beneath which navigation becomes increasingly challenging. The MNCD, in contrast, indicates the targeted minimum depth that should be maintained within the navigable channel to ensure the safe passage of barges. Figure 5 illustrates these navigational concepts using Kaub in the Middle Rhine as a reference case.

For the last two localities in the Upper Rhine, the EWL data are not directly accessible. Table 1 compares the EWL with two different percentiles of daily water levels, showing that the EWL closely aligns with the fifth percentile of this distribution (i.e., p05). This criterion allows us to approximate the EWL for Kronenhof and Rheinweiler. Additionally, high water levels become a navigational concern when they approach the minimum clearance levels under bridges. We establish a threshold above which water conditions are considered critical for safe navigation by applying a symmetric approach to the EWL, i.e., adopting the 95th percentile (p95) of the statistical distribution.

In addition to considering the occurrence of critical water levels (CWL), these threshold values are used to calculate the number of days experiencing critically low (LWL) and critically high water levels (HWL) along the Rhine. As noted in the previous section, two exceptional throughput disruptions warrant further attention in the time series. The first is the Waldhof accident on the Middle Rhine,

ARTICLE IN PRESS

Table 2
Descriptive statistics, 2000 – 2022

Variable	Unit	Mean	SD	Min	Max
Throughput	TEUs	158,238.80	26,666.26	94,534.00	224,524.80
CWL	Binary	0.64	0.48	0.00	1.00
LWL	Days	4.63	8.93	0.00	31.00
HWL	Days	2.97	5.71	0.00	30.00
Waldhof	Binary	0.00	0.06	0.00	1.00
Sustained LWL	Binary	0.01	0.08	0.00	1.00
German MIP	Index	93.30	8.49	71.40	107.80
Swiss I&E	Billion USD	28.93	9.25	12.02	46.98

Notes: Manufactures Industrial Production (MIP). Index with reference 2015 = 100. I&E: Imports and Exports

Table 3
Hydrological scenarios linked to climate change

Scenario	Global temperature increase in 2050 (°C)	Change of atmospheric circulation	Average annual number of low water days
M	+1	Weak	104
M+	+1	Strong	147
W	+2	Weak	100
W+	+2	Strong	191
Baseline			56
2018			130

Source: Deltares (2023); Jonkeren et al. (2011); KNMI (2023); Rijkswaterstaat (2023); Te Linde (2007).
Notes: Baseline compromises the entire study period (2000 – 2022).

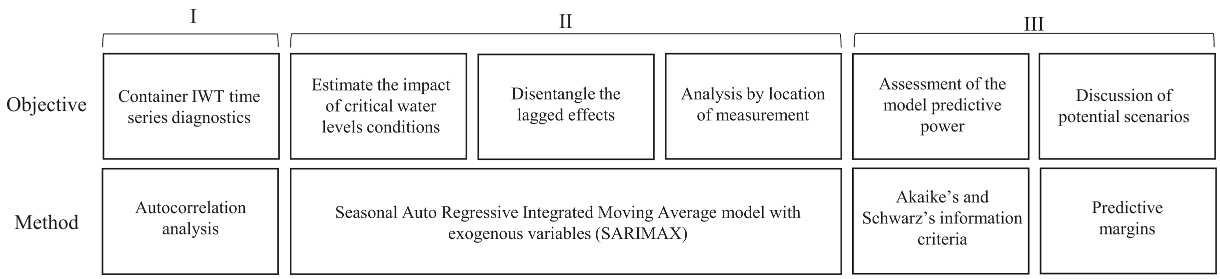


Figure 6. Analysis framework

which disrupted navigability near Kaub. The second is the sustained period of low water levels in 2018, which was followed by the largest loss of market share in recent decades (Eurostat, 2023). Therefore, we introduce two binary variables to capture the disruption in container throughput caused by these events. The first binary variable (Waldhof) is assigned a value of 1 in January 2011. The second binary variable (Sustained LWL) is assigned a value of 1 in October and November of 2018, and 0 for other periods.

Furthermore, we include monthly data on two critical macroeconomic indicators: the Manufactures Industrial Production Index of Germany (German MIP) and Switzerland's total imports and exports (Swiss I&E), which are recognized as strong predictors of container IWT demand due to the Rhine's integration into the German and Swiss trade infrastructures (Van Meir et al., 2022). Descriptive statistics for the variables in the model from January 2000 to December 2022 are reported in Table 2. Notably, the number of days with critically low water levels exceeds the number of days with critically high water levels. Additionally, the standard deviation is around nine days for low levels and six days for high levels, which is approximately double their respective mean values.

Finally, we utilize the expected number of days with critically low water levels from existing literature (Jonkeren et al., 2011; Te Linde, 2007), updated with the implications of the latest climate change scenarios for the discharge regime of the Rhine (Deltares, 2023; Rijkswaterstaat, 2023). The research related to these scenarios ensures its applicability for the Dutch transboundary river basins (KNMI, 2023). In terms of days with critically low water levels at the transport corridor, the scenarios published by KNMI can be summarized by combining changes in global temperature and atmospheric circulation for 2050 (Jonkeren et al., 2011; Te Linde, 2007). Adopting the notation from existing literature, the letter M represents *Moderate*, and W represents *Warm*. The symbol + indicates a strong change in atmospheric circulation (Table 3). We leverage these scenarios to conduct predictive margins on container throughput based on the average annual number of days with low water levels associated with each potential case. The baseline considers the number of days with such conditions throughout the entire study timeframe (2000 – 2022).

3.1. Analysis framework

To analyze the effects of critical water levels on container transport along the Rhine and discuss resilience policies, we employ a three-part analysis framework as outlined in Figure 6. (I) The process begins with a time series assessment that utilizes the correlogram of monthly container IWT to identify all significant serial and seasonal patterns. (II) The information collected is then used to develop an econometric model that evaluates the immediate and lagged impacts of days with critical water level conditions on container IWT throughput across the nine locations along the Rhine. (III) Finally, we use predictive margins to estimate potential throughput variations under various climate change scenarios. The following sections provide a more detailed explanation of each part of this analysis framework.

3.2. Time series diagnostics

The general form of the model is presented in **Eq. (1)**. The dependent variable is the logarithm of monthly container throughput transported in the Rhine. The independent variables are captured in a vector that includes the occurrence of CWL, the number of days with critically low and high water levels (i.e., LWL and HWL, respectively), the Waldhof accident, the sustained period of low water levels in 2018, the German MIP, and Swiss I&E. Furthermore, as depicted in Figure 2, the time series exhibits a positive trend up to 2018, followed by a negative trend, and may also be influenced by seasonal effects.

These temporal patterns must be modeled to avoid bias in estimating the effects associated with critical water level conditions. To achieve this, we consider the lagged components of dependent and independent variables, as represented by the summation terms in **Eq. (1)**. The order of p and q will be determined by diagnosing the autocorrelation (AC) and partial autocorrelation diagrams (PAC). Based on the correlogram (see **Appendix A**), we incorporate these trends when specifying the form of the econometric model in the next section. The coefficients obtained for the set of variables in x (i.e., $\widehat{\beta}$) are interpreted as semi-elasticities, with the exception of Swiss I&E, which is interpreted as an elasticity.

$$y_t = x_t\beta + \sum_{i=1}^{p}\rho_i(y_{t-i} - x_{t-i}\beta) + \sum_{j=1}^{q}\theta_j\varepsilon_{t-j} + \varepsilon_t \tag{1}$$

Where:

. y_t is the logarithm of total TEUs transported in the traditional Rhine during month t.
. x_t denotes a vector containing CWL, LWL, HWL, Waldhof, Sustained LWL, German MIP, and the logarithm of Swiss I&E.
. ε_t represents the remaining disturbances.
. $\beta, \rho,$ and θ are the parameters to be estimated.

3.3. Model specification

We fit a Seasonal Auto-Regressive Integrated Moving Average model with Exogenous variables (SARIMAX) in the form $(0,1,1)(0,1,1)_{12}$ as depicted in **Eq. (2)**. Following the considerations of Box et al. (2008), this model applies the first difference to address any non-stationarity in the time series and a difference of order 12 to capture the identified seasonal pattern. The modeling of the moving average (MA) components introduces a multiplicative term that accounts for a non-stationary trend in the seasonal effect. As this term does not provide a meaningful interpretation, it will not be included in the results tables. The estimation of this model is conducted via maximum likelihood (Hamilton, 1994). The likelihood function to be optimized assumes a normal distribution of the predicted disturbance, as represented by **Eq. (3)**.

$$\Delta\Delta_{12}y_t = (1+\rho L)\Delta\Delta_{12}x_t\beta + (1+\theta L)\left(1+\theta_{12,1}L^{12}\right)\varepsilon_t \tag{2}$$

$$lnLL_t = -\frac{1}{2}\left\{\ln(2\pi) + \ln(|M_t|) - \widehat{\varepsilon}_t^{'}\mathrm{M}_t^{-1}\widehat{\varepsilon}_t\right\} \tag{3}$$

Where:

. Δ denotes the first difference operator, capturing the nonstationary of the time series.
. Δ_{12} accounts for the annual seasonal pattern.
. L represents the lag operator.
. LL_t denotes the likelihood function.
. M_t is the mean squared error.
. $\widehat{\varepsilon}_t$ accounts for the predicted disturbance.

For a comprehensive analysis of the results, we sequentially estimate the econometric model from its simplest to its most complex form. First, we test the significance of the seasonal and MA components. Second, we incorporate the occurrence of critical water levels at any of the nine locations (i.e., CWL). Third, we examine the incidence of those episodes by the number of weeks and days per month, disaggregating by LWL and HWL. Fourth, we evaluate lagged effects on container throughput in subsequent months. Fifth, the model is estimated with data from 2018 to 2022 to assess whether the impact has evolved in recent years.

Table 4
General SARIMAX results

	(I)	(II)	(III)	(IV)	(V)
CWL		-0.014*			
		(0.008)			
LWL			-0.003***	-0.002***	-0.005***
			(0.001)	(0.001)	(0.001)
HWL			-0.002***	-0.002***	-0.005***
			(0.001)	(0.001)	(0.002)
LWL (t-1)				-0.002***	-0.001
				(0.001)	(0.001)
HWL (t-1)				-0.001	0.001
				(0.001)	(0.002)
MA (t-1)	-0.400***	-0.405***	-0.451***	-0.456***	0.106
	(0.130)	(0.130)	(0.112)	(0.102)	(0.318)
MA (t-12)	-1.103***	-1.099***	-0.891***	-0.911***	-1.002***
	(0.058)	(0.060)	(0.045)	(0.053)	(0.368)
σ	0.066***	0.065***	0.069***	0.067***	0.075***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.015)
Log-Likelihood	307.04	308.44	321.86	325.81	59.58
Observations	263	263	263	262	60

Notes: Coefficients outside parenthesis. Robust standard errors inside parenthesis.
$p < 0.1$ *, $p < 0.05$ **, $p < 001$ ***

To explore spatial patterns, we analyze each of the nine locations separately. This approach enables us to disentangle the spatial differences of LWL and HWL and also to account for the standard deviation of daily water levels at each location. Finally, we incorporate the remaining control variables related to macroeconomic conditions and other disruptive events (i.e., German MIP, Swiss I&E, Waldhof, and Sustained LWL). Similarly, the set of estimations is conducted sequentially as robustness checks before proceeding with the predictive analysis.

3.4. Predictive analysis

We employ the SARIMAX model to make predictions based on climate change scenarios. To select the model with the highest predictive quality, we use the complete dataset and compare the models using Akaike's Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC), which balance the models' goodness-of-fit and complexity (**Eq. 4**). In practice, these criteria favor a higher value of the log-likelihood function and impose penalties for a larger number of parameters to be estimated. A lower score indicates a better model. The penalization component is the main difference between the two criteria; thus, we use both as complementary checks to select the more accurate predictive model.

$$AIC = -2lnLL + 2k \tag{4.1}$$

$$BIC = -2lnLL + klnN \tag{4.2}$$

Where:
. $lnLL$ is the maximized log-likelihood of the model.
. k denotes the number of parameters to be estimated.
. N indicates the sample size.

Based on the AIC and BIC criteria, the coefficients obtained from the best model are used to conduct predictive margins under various water level scenarios. First, the MA components are estimated using past disturbances, as outlined in **Eq. (5)**. Next, we calculate the predicted throughput by fitting the number of days with critically low water levels indicated in scenario S_i, reflecting changes in global temperature and atmospheric circulation. Finally, the prediction is compared to a baseline scenario that considers the average number of days with critically low water levels between 2000 and 2022, as represented by **Eq. (6)**.

$$z_t = f(x_t, \hat{\varepsilon}_t, \beta, \theta) = (1 + pL)\Delta\Delta_{12}x_t\beta + \theta L\left(1 + \theta_{12,1}L^{12}\right)\hat{\varepsilon}_t; \tag{5.1}$$

$$\hat{\varepsilon}_{t-j} = \begin{cases} \Delta\Delta_{12}y_{t-j} - z_{t-j}, t-j > 0 \\ 0, otherwise \end{cases} \tag{5.2}$$

$$PAV_i = \hat{p} - \hat{p}_i = \frac{1}{n}\left[\sum_{t=j}^{T} f(x_t, \hat{\varepsilon}_t, \hat{\beta}, \hat{\theta}|\overline{LWL}) - \sum_{t=j}^{T} f(x_t, \hat{\varepsilon}_t, \hat{\beta}, \hat{\theta}|LWL = S_i)\right] \tag{6}$$

Where:
. $\hat{p}$ is the predicted margin at mean values and $\hat{p}_i$ is the predicted margin under climate change scenario i : M, M+, W, or W+.
. S_i is the average number of days with low water levels under each scenario.

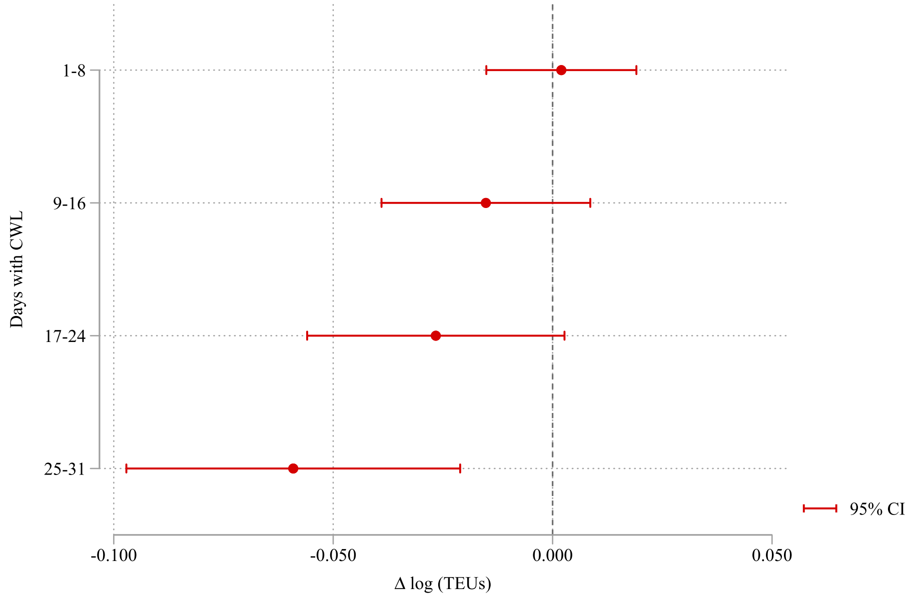


Figure 7. Semi-elasticity of event occurrence (CWL) by days of duration. Note: Confidence interval (CI).

. PAV_i represents the predicted average variation of throughput under scenario i compared to the baseline case.
. n are the number of months with data left after controlling for nonstationary trends (i.e., Δ_{12} and Δ), and lagged effects (i.e., Lx_t).

4. Results

Between 2000 and 2022, 185 months (64%) experienced at least one day with critical water levels, with an average duration of eight days. Table 4 presents the results from the SARIMAX model, assessing sequentially the average impact on container IWT. First, Column I validates the significance of the yearly seasonal pattern in container IWT and its first-order MA component. This suggests that approximately 40% of a disturbance in month t will most likely be reflected in month $t+1$ and during the same month one year ahead ($t+12$). To quantify the average effect of such disturbances, the parameter σ indicates a standard deviation of around 7%. In container terms, this finding translates to a typical monthly disturbance of approximately 11 thousand TEUs between 2000 and 2022. This disturbance can impact container IWT through various mechanisms, such as limiting capacity or inducing modal shift.

In Columns II to V of Table 4, we assess the specific impact of critical water level conditions at the complete set of nine locations. Column II indicates that the occurrence of CWL precipitates an average loss of 1.4% in container throughput, and the parameter is significant at the 90% confidence level. However, this estimation does not account for the duration of the occurrence. In other words, longer episodes are expected to precipitate a more significant impact compared to shorter ones. To explore duration effects, we assess the number of weeks and days with reported critical water level conditions. Figure 7 examines the occurrence of critical water levels by week of duration. It suggests that the degree of disruption caused by CWL on container IWT increases with longer periods. After 24 days, the average impact is a decrease of 5.9% at the 95% confidence level.

Within this framework, Columns III and IV explore the duration of occurrences by the number of days with critically low and high water levels (i.e., LWL and HWL, respectively). The results show that each additional day with critical water level conditions is associated with an average decrease of 0.2% in throughput during the same month. Moreover, we observe a lagged effect in the following month for low water level conditions, but not for high water levels. Finally, Column V focuses on the observations from 2018 to 2022, showing that the disruptive effect is approximately double during this period. It is also noteworthy that we tested for quadratic effects, but the results were not statistically significant.

Furthermore, we explore the differentiated effects of critical water levels on container IWT by the location in which the disruption occurs. Figure 8 shows that the number of critical days is higher in the locations of the Upper Rhine, which decreases in locations closer to the North Sea. This is explained by the river's original hydrological sources being closer to the Upper Rhine, with its flow increasing downstream. In the Upper Rhine segment, the waterway is relatively narrow, leading to less variation and a higher number of days with LWL. For locations in the Middle and Lower Rhine, both the median values and variability levels are higher, as illustrated by the color intensity in Figure 8. Conducting the analysis by location allows us to disentangle the role of water level variability from the occurrence and duration of critical conditions along the transport network.

The distribution of water levels across the nine locations is depicted in Figure 9. Notably, the median levels are lower in the Upper Rhine, with Rheinweiler recording the lowest median of approximately two meters. As the Rhine flows towards the North Sea, there is a general increase in median water levels. An exception is Maxau, which exhibits the highest median water level of approximately five meters. The unique morphology of the waterway at this location explains this deviation from the general trend. Further downstream,

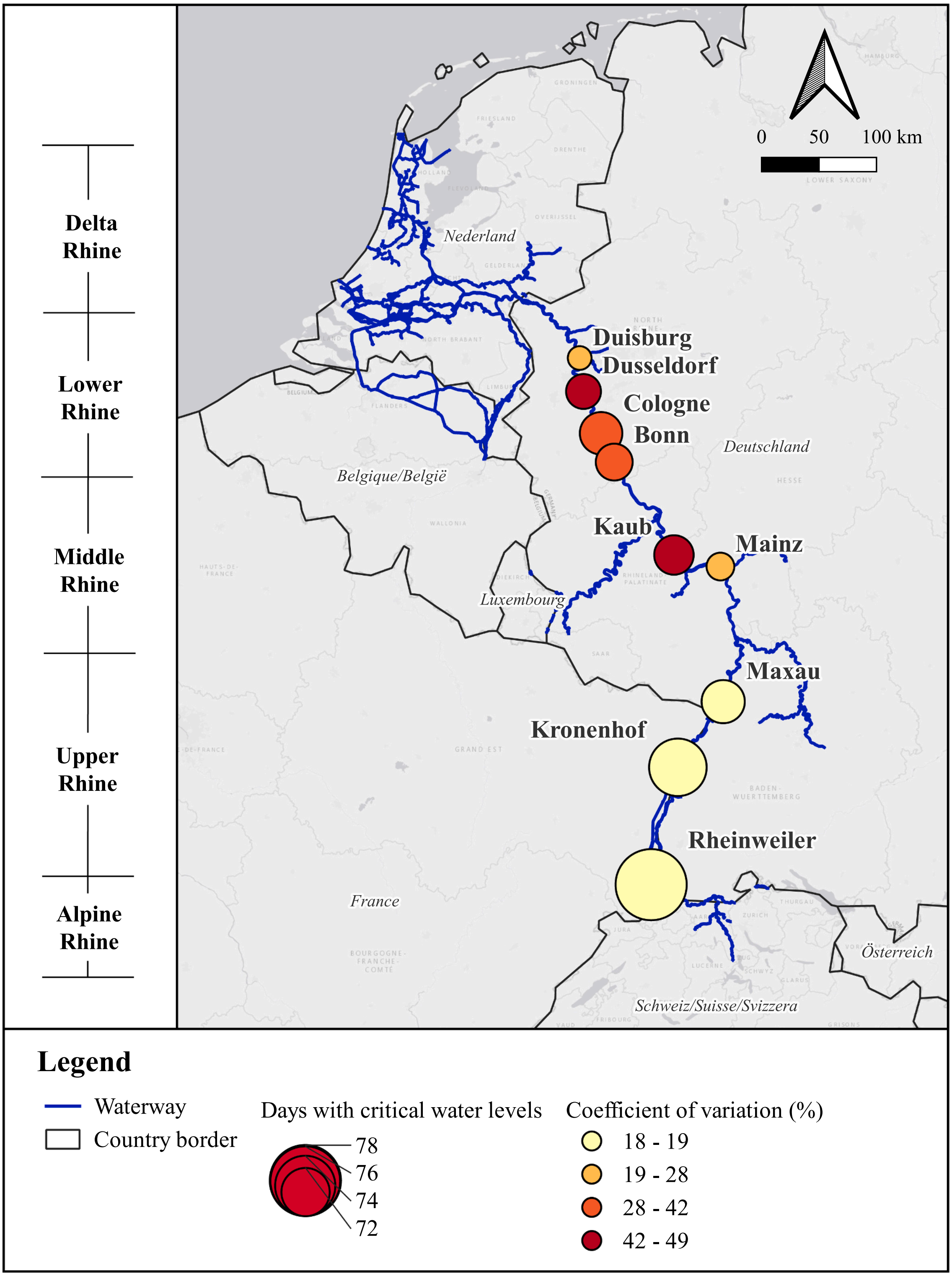


Figure 8. Water level conditions per location (2000 – 2022)

Duisburg, located in the Lower Rhine, has the next highest median of around four meters. The levels at the other locations are below the 3.5-meter median mark.

The variability in water levels is positively correlated with higher median levels, particularly in the Lower Rhine (right panel of

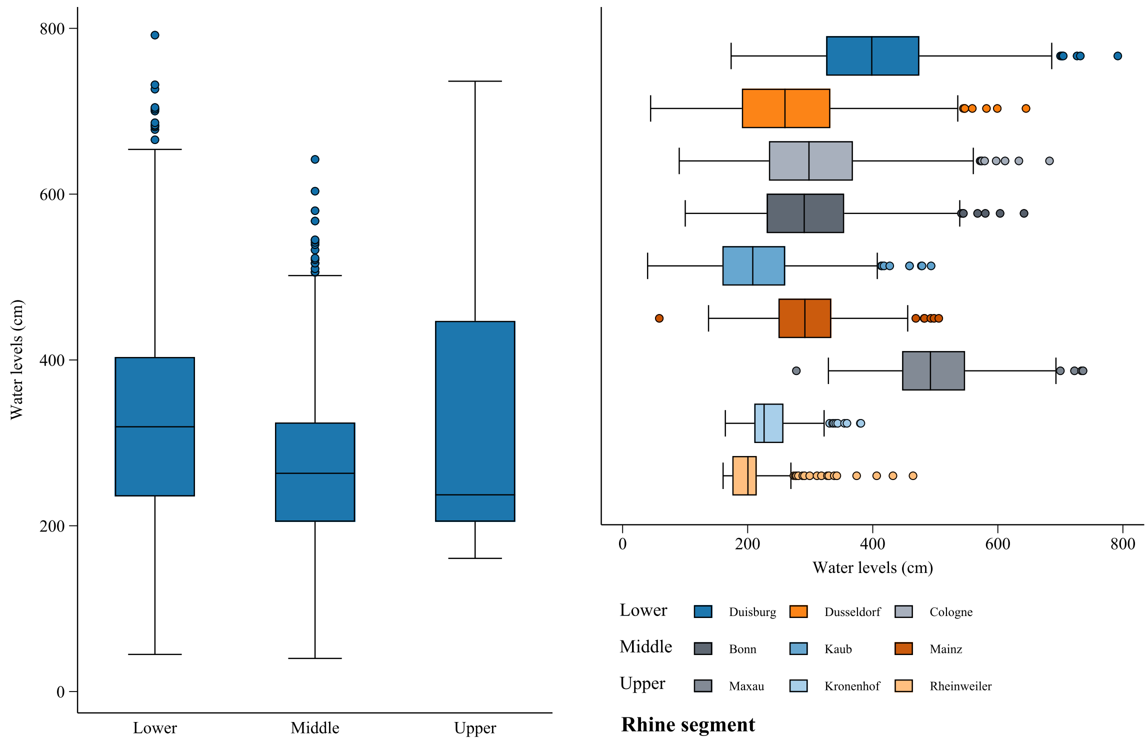


Figure 9. Distribution of daily water levels per location

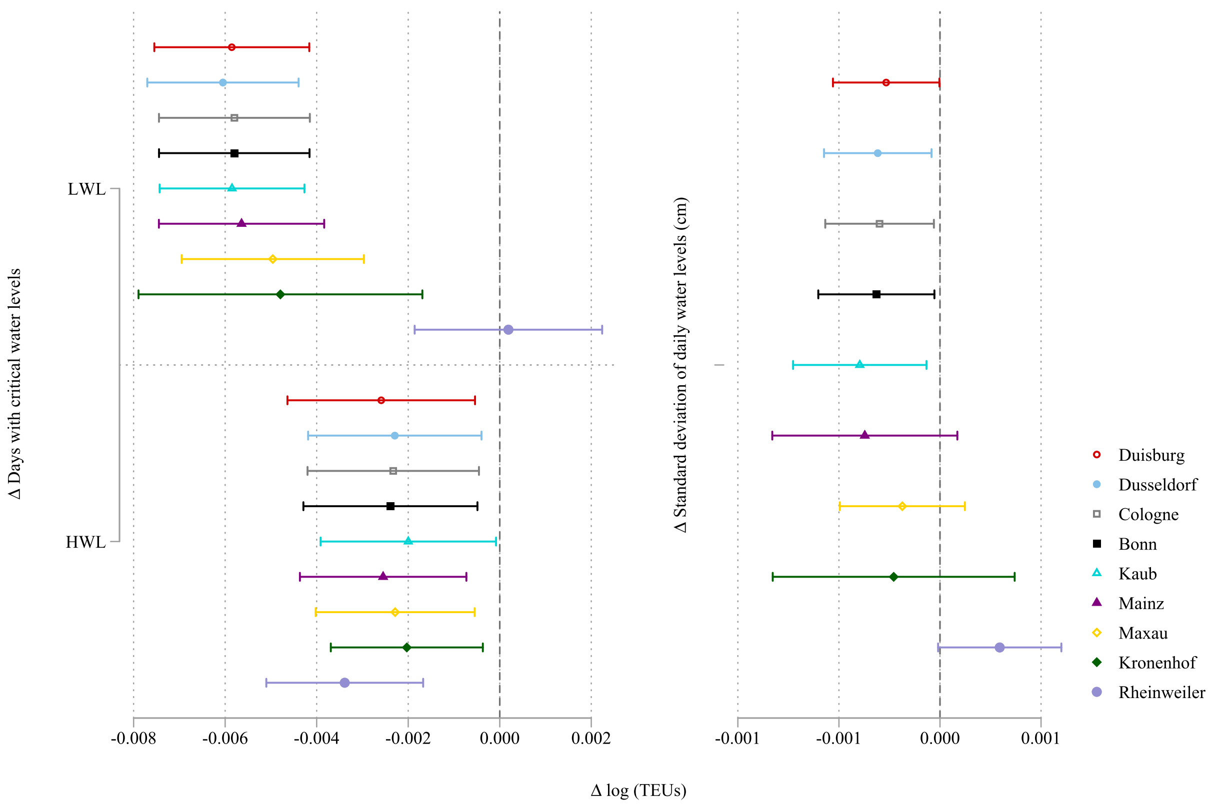


Figure 10. Localized effects

Table 5
Robustness checks

	(VI)	(VII)	(VIII)	(IX)
LWL	-0.002***	-0.002***	-0.002***	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)
HWL	-0.002***	-0.002***	-0.002***	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)
LWL (t-1)	-0.002***	-0.002**	-0.001**	-0.001**
	(0.001)	(0.001)	(0.001)	(0.001)
HWL (t-1)	-0.001	-0.000	0.000	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)
Waldhof	-0.236***	-0.239***	-0.249***	-0.241***
	(0.056)	(0.052)	(0.058)	(0.059)
Sustained LWL		-0.216**	-0.228***	-0.232***
		(0.091)	(0.088)	(0.088)
German MIP			0.008***	0.005**
			(0.002)	(0.002)
Swiss I&E				0.333***
				(0.083)
Log-Likelihood	334.69	345.72	358.81	364.42
Observations	262	262	262	262

Notes: SARIMAX results. Semi-elasticities outside parenthesis. Swiss I&E in logarithm.
Robust standard errors inside parenthesis. $p < 0.1$ *, $p < 0.05$ **, $p < 001$ ***

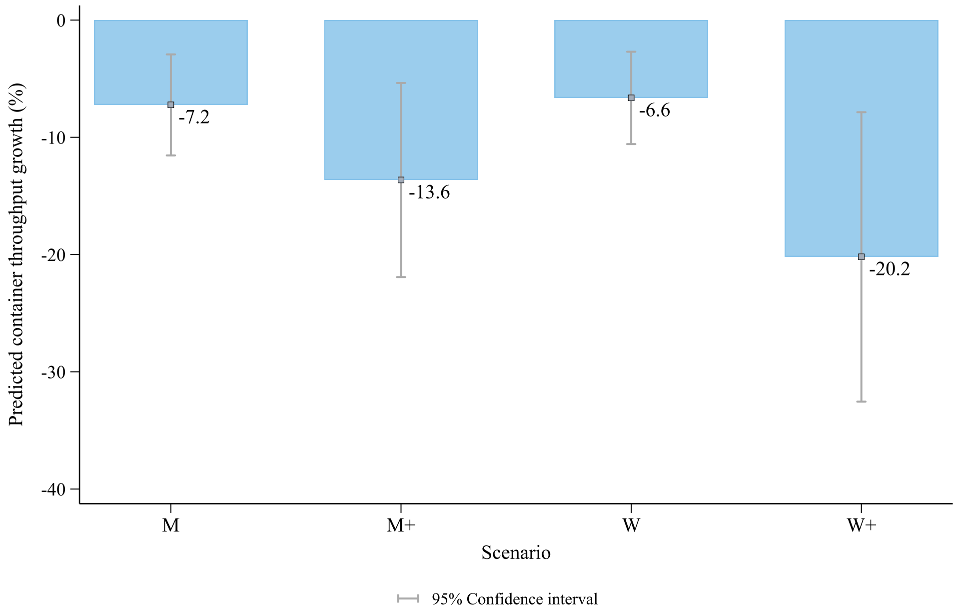


Figure 11. Predictive margins on climate change scenarios for 2050. Notes: Relative change compared to the baseline scenario (2000-2022).

Figure 9). The range between the lower and upper quartiles of the distribution expands with increasing water levels, indicating greater unpredictability at these locations. The standard deviation is the lowest in Rheinweiler, at 55 cm, and reaches a maximum in Duisburg, at 139 cm. Furthermore, instances of statistically atypically high water levels occur more frequently than instances of low levels. The two cases of atypical low water levels are recorded in Mainz and Maxau. However, these outliers become less pronounced when aggregating the data by Rhine segment, as shown in the left panel of Figure 9. Thus, while individual locations may experience exceptionally low water events, these are not necessarily replicated at other nearby locations within the segment.

The results from the SARIMAX model assessing localized effects are presented in Figure 10. While the impact of critically high water levels remains similar to the general model in Table 4 (i.e., -0.2%), we found that the effect of critically low conditions is considerably more substantial, averaging around -0.6%. This result is consistent across the Lower and Middle Rhine segments. In these locations, prolonged navigability disruptions significantly affect a larger proportion of container flows between the ports and the hinterlands in Germany, Luxembourg, France, and Switzerland. Additionally, we note that the impact loses statistical significance at Kronenhof and Rheinweiler in the Upper Rhine, as these are not central points for cargo flows in the transport network. The impact of higher daily water level variability is significant for locations up to Kaub in the Middle Rhine, with a coefficient close to -0.05%. Finally, we found that the lagged localized effect is statistically significant concerning critically low water conditions at the same locations, aligning with

-0.2%. However, the lagged effect does not appear statistically significant following high water levels or increased variability.

For further robustness checks, the consistency of the estimates is tested sequentially with the rest of the control variables, as detailed in Table 5. From models VI to IX, the coefficients associated with the number of days with critical water level conditions remain robust after including the Waldhof accident, the episode of sustained LWL, the German MIP, and Swiss I&E. Notably, these control variables are statistically significant predictors of container IWT. In the most comprehensive model (IX), the semi-elasticity of the German MIP index is estimated at 0.5%, while the elasticity of Swiss I&E is at 0.33%. The significance of Swiss international trade can be attributed to the Rhine being the only navigable waterway that provides access to the deep seaports in the North Sea.

The best fit of the model is achieved in Column IX, which has the highest log-likelihood. However, assessing the models based solely on log-likelihood does not account for model complexity. With an increased number of parameters to estimate, the predictive quality of the model can weaken. For example, including disaggregated measures per location is significantly penalized by the BIC criteria. Therefore, we compare the models presented in Columns I-IX, considering the total number of days with critical water situations across all network locations. Model V is naturally excluded as it covers a different timeframe (i.e., 2018-2022) than the rest of the models. The analysis confirms that the most comprehensive model (IX) achieves the best performance without suffering from overfitting (see **Appendix B**).

Consequently, we utilize model IX to derive the predictive margins for each of the climate change scenarios. Figure 11 illustrates the potential average losses for 2050 compared to the reference case. In the least adverse scenario, which assumes a global temperature rise of 2 degrees and a weak change in atmospheric circulation, the predictive margin suggests an average potential loss of 7.2% average annual for container IWT. In the worst-case scenario, which entails a temperature rise of 2 degrees and a strong change in atmospheric circulation, the predicted loss escalates to 20.2%. When expressed in TEUs, the predicted potential monthly average losses range from 11.7 to 32.6 thousand.

5. Discussion and policy implications

While rail transport and heavy goods vehicles generate external costs equivalent to 0.04% and 0.52% of the EU28 GDP, respectively, the external costs associated with IWT are only 0.02% (European Commission, 2019). Consequently, the potential sustainable benefits of increasing the use of IWT have been a focal point of European policy agendas over the past decades. The Transport White Paper indicated that around 30% of road freight transport over distances greater than 300 km should shift to more sustainable alternatives by 2030, and 50% by 2050 (European Commission, 2011). Various EU programs have been launched to promote the sustainable development of combined freight transport, including TEN-T, Motorways of the Sea, the Combined Transport Directive, and Horizon Europe (Björk et al., 2023; European Parliament, 2022).

Despite rail transport generating less NOx, PM, and greenhouse gases than IWT in Europe (Kendra et al., 2023), IWT is the only sustainable mode with sufficient spare capacity for significant market uptake in the region for container cargo transported over long port-hinterland connections (European Commission, 2017). To contribute to the sustainable development of freight transport, IWT should not be limited to moving commodities such as crude oil, coal, iron ore, dry bulk, sand, and gravel, but should also increase its role in regional container transport (CCNR, 2022a). However, no significant gains in modal split were achieved before 2015 within the EU, and a negative trend has been observed since the sustained period of low water levels in 2018 (ECA, 2015; Eurostat, 2023b).

The occurrence and duration of critical water levels could continue to hinder the advantages of container IWT in Europe. As the traditional Rhine is classified as CEMT-VI (EURIS, 2024), large barges can be utilized to reach the most distant hinterlands within the IWT network (e.g., Basel, Switzerland). However, these advantages are compromised during periods of critical water levels, as the loading capacity of vessels is reduced, and smaller vessels may become more attractive alternatives for navigating towards the hinterland (Schweighofer et al., 2022).

The recently updated climate change scenarios suggest an increase in the frequency and duration of critical water levels (KNMI, 2023). Specifically, for the Rhine, rising temperatures will lead to the gradual melting of glaciers in the Alps, resulting in a reduction in snowpack thickness over the century. Consequently, this will cause higher winter discharge rates, while the contribution of meltwater to the Rhine will decrease, leading to lower river discharges during the summer half-year (Deltares, 2023; Rijkswaterstaat, 2023). Such findings are critically relevant to our research, indicating that we can expect not only critically low water levels but also critically high water levels and greater overall fluctuations in water levels, as examined in this study.

The impact of critical water levels is disentangled in this research by isolating confounding temporal trends, seasonality, and other influencing factors. For instance, our results suggest that Swiss trade and German manufacturing production are strong predictors of container IWT in the Rhine. In this context, critical water levels can affect not only upstream flows from the seaports but also impact downstream container flows, such as Swiss exports. Since the container market is more time-sensitive than other cargo segments, effective policymaking is required to prevent further losses in IWT within the container market due to the incidence of critical water levels.

Notably, the modal share of IWT has declined by around 20% since the dry summer of 2015, with a loss of 11% occurring in 2018 alone (Eurostat, 2023b). This research demonstrates that systematically studying the occurrence of new episodes of critical water levels provides insightful examples of the observed negative trend in modal split. In terms of TEUs, the results from the econometric approach indicate a 23% decrease in container throughput following the sustained period of low water levels in 2018. Furthermore, the results suggest that the impact of new episodes has doubled, reaching -0.5% container throughput per disruptive day since that year. The most recent observed episode in our timeframe occurred during the summer of 2022. Given the uncertainty of climate change, we estimate potential annual average losses between 7 and 20% for 2050, indicating that achieving a market capture of IWT is unlikely if the current trend continues.

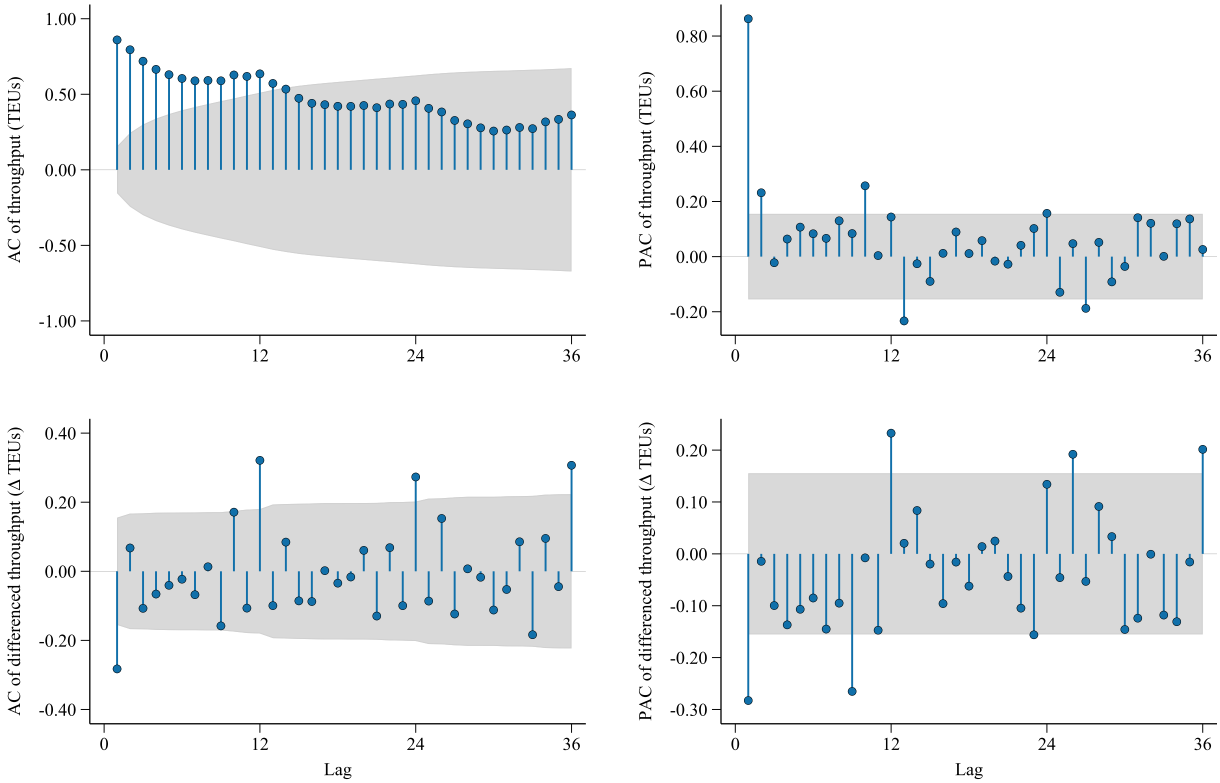


Figure 12. Correlogram. Notes: Autocorrelation (AC), Partial Autocorrelation (PAC). Confidence intervals at the 99% level of significance.

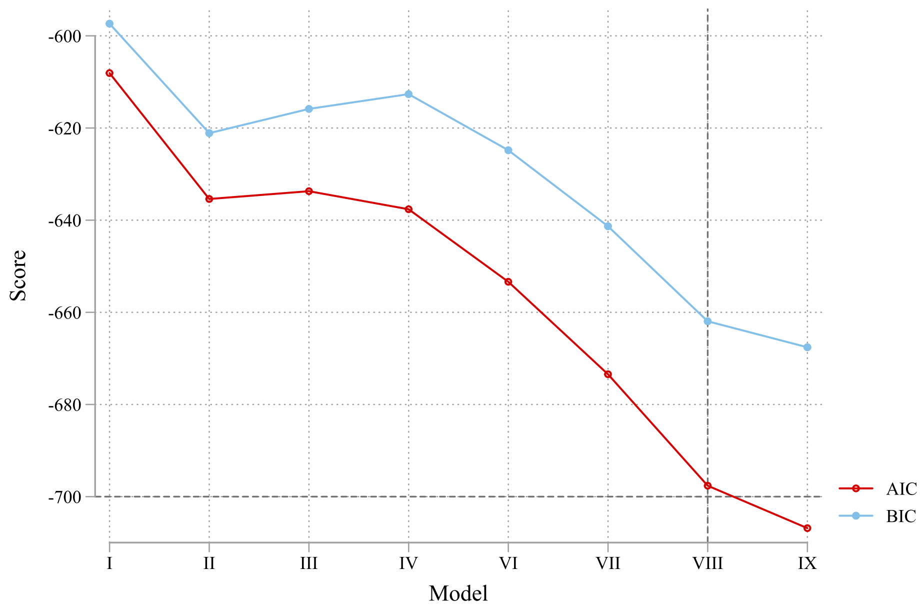


Figure 13. Information criteria for model selection

Nonetheless, innovative developments and informed resilience policies can contribute to reversing the current negative trend in the market share of IWT. Many of these policies have been discussed by stakeholders but require effective implementation to enhance the reliability of IWT during future critical water level situations. Among the feasible mid-to-long-term policies are the design and construction of innovative vessels capable of operating in low water conditions and optimizing cargo loading, as well as infrastructure upgrades that include optimized use of locks and the creation of new storage capacities (Novimove, 2023).

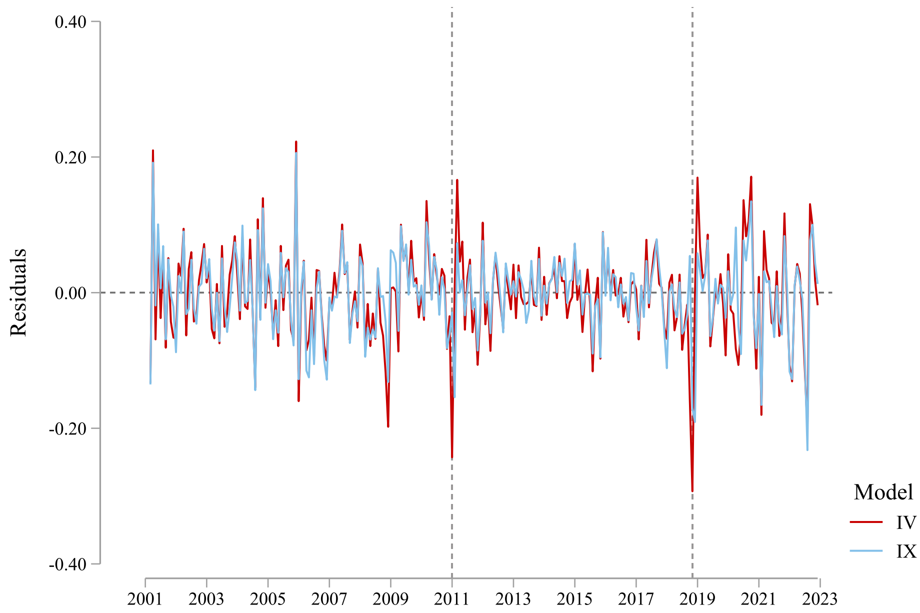


Figure 14. Predicted residuals

The main contributions of this paper provide insights into short-term resilience policymaking for container IWT, one of the least studied segments. Our results show that this type of IWT is significantly influenced by disturbances from the previous month and follows a yearly seasonal trend. Therefore, stakeholders must consider the lagged effects of unfavorable macroeconomic conditions, geopolitical tensions, or accidents that disrupt navigation. Additionally, the impact of one day with critically low water level conditions was found to be -0.2% during the same month, with a continued impact of -0.1% on average in the following month.

The time component of the approach can be leveraged to take informed decisions over new episodes of critical water levels. First, it informs stakeholders about the potential impacts of newly emerging droughts and the consequences if the duration extends beyond a certain period. Second, regarding the time to respond, the results indicate a critical three-week window for implementing measures before the event significantly reduces monthly throughput. For example, as a response policy, stakeholders could establish temporary agreements with alternative transport modes until water levels return to navigable conditions, employing synchromodal concepts. This strategy aims to prevent permanent losses due to modal shifts. Third, in terms of recovery time post-disruption, the approach recommends considering an additional month before expecting a rebound in container cargo flows following episodes of critically low water levels. Conversely, no additional months are required for recovery from critically high water levels according to the study findings. These insights can assist in adjusting expectations and formulating responses at both the shipper and transport operator levels.

Fourth, reducing water variability in the locations of the Lower and Middle segments of the Rhine could help avoid an average impact of -0.05% per disruptive day. Available alternatives include developing digital solutions that provide boat masters with up-to-date information about navigable channel depth, improving voyage planning, and enhancing coordination between logistics partners (COVADEM, 2023). Furthermore, maintenance of waterway infrastructure and sustainable water management strategies can contribute to more stable channel conditions during low water levels. It is essential to always consider the various uses of the Rhine, including habitat preservation, drinking water sources, and recreational spaces (CCNR, 2021).

Fifth, improved forecasting tools could be leveraged to facilitate timely responses to new episodes of dry weather. Our results regarding the temporal patterns of significant disruptions in water levels suggest that forecasts should ideally be made at least three weeks before the occurrence of critically low water levels. The forecasts must highlight the variability patterns at critical locations in the Middle and Lower Rhine up to Kaub. A tool that integrates and shares such information could be a valuable asset for the sector by reducing uncertainty regarding hydrological conditions, enabling informed actions at both the shipper and transport operator levels.

The paper has limitations that must be acknowledged. Firstly, it focuses solely on container IWT and does not capture the multimodal relationships in the Rhine. Further analysis could be conducted to understand complementary and substitution patterns following disruptions in critical water level conditions, considering the competitive landscape. All the NUTS-2 regions involved in the traditional Rhine meet the criteria for IWT to compete with road and rail transport in port-hinterland connections. Specifically, these are regions connected to a CEMT-IV class inland waterway network that can be accessed by road over a maximum distance of 100 km (European Commission, 2017).

On the other hand, the estimation of predicted margins is subject to established hydrological scenarios, which may evolve due to rapidly changing climate patterns. The study outlines average losses for four potential scenarios in 2050 at the corridor level, which should be interpreted with caution. Additionally, the predictive margins do not consider technological advancements that could enhance resilience against similar disruptions, potentially mitigating the impact of critical water levels on container IWT. Therefore, further research is needed to evaluate the effects of innovative developments and the implementation of resilience policies on the Rhine inland network. Lastly, the research focuses on total container throughput, without disaggregating the impact by the type of product within containers or drawing conclusions on empty container repositioning. Future research could extend the proposed approach to examine the impact on specific cargo segments.

6. Conclusions

The potential of IWT to mitigate the external costs of transport and promote regional integration in Europe has been hindered by the occurrence and duration of critical water level conditions. This paper uncovers the temporal and spatial patterns of the impact that new episodes have had on container throughput in the Rhine between 2000 and 2022. First, we show that container IWT exhibits a yearly seasonal pattern and is also significantly affected by disturbances from the previous month, including the duration of critically low water level conditions.

Second, the average impact on monthly container throughput is -0.2% per day with critical high or low water levels in the Rhine. The impact escalates to -5.9% for sustained periods of more than 24 days per month. Additionally, the effect exhibits spatial variation. The impact of low water levels increases to -0.6% per day with localized critical conditions. In the Middle and Lower Rhine, one additional standard deviation in daily water levels is associated with an effect of -0.05%.

Third, we observe that the impact has doubled since 2018 and could be further exacerbated by climate change. Considering various scenarios of global temperature rise and atmospheric circulation changes, the potential annual average losses in throughput for 2050 range between 7% and 20%. Resilience policymaking will be essential to enhance the reliability of IWT and maintain the Rhine as a competitive navigable transport corridor in Europe. With sufficient information, time, and viable alternatives, stakeholders can make more sustainable mode choice decisions and avoid higher external costs that European communities along the inland network would assume.

CRediT authorship contribution statement

Felipe Bedoya-Maya: Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Validation, Visualization, Writing – original draft. **Peter Shobayo:** Writing – review & editing, Validation. **Joris Beckers:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Edwin van Hassel:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research is part of the European Union's Horizon 2020 Novimove project, with grant No. 858508. We are grateful to Destatis and CCNR for providing the data necessary to conduct this research.

Appendix

A. SARIMAX specification

The correlogram in Figure 12 suggests evidence of a yearly seasonal effect, which is an intuitive cyclic pattern of IWT. The analysis also indicates an MA effect of the first order, confirmed by the PAC. This pattern can be explained by the susceptibility of container IWT to the disturbance events that occurred during the previous month. Finally, it also reports evidence of a negative response of throughput close to the end of the first year, which can be interpreted as an anticipation of the yearly seasonal pattern.

B. Information criteria for model selection

Figure 13 reports the AIC and BIC information criteria for model selection. The results indicate penalization after including the lagged effects of critical water levels, especially according to the BIC (models III and IV). Nonetheless, the goodness-of-fit improves remarkably after including the rest of the control variables. The most complete model (IX) achieves the best performance without suffering from overfitting. As a relative analysis, from a starting AIC score of -608 and BIC of -597, the last performance surpasses -705 and -665 in model IX, respectively.

We further assess the goodness-of-fit in terms of the predicted disturbances. Figure 14 compares models IV and IX, the two most complete per section of the analysis. The results suggest that the standard deviation of disturbances decreased by around 13% in the latter. Accounting for macroeconomic conditions presents benefits in reducing the residual disturbances during the entire study

ARTICLE IN PRESS

timeframe. Moreover, significant gains are observed between the two models concerning the Waldhof accident in Jan 2011 and the sustained period with low water levels at the end of 2018, making the residuals fall below the -0.2 to 2.0 bandwidth.

References

Bedoya-Maya, F., Beckers, J., van Hassel, E., 2023. Spillover effects from inland waterway transport development: Spatial assessment of the Rhine-Alpine Corridor. J. Transp. Geogr. 113, 103721 https://doi.org/10.1016/j.jtrangeo.2023.103721.

Björk, L., Vierth, I., Cullinane, K., 2023. Freight modal shift: A means or an objective in achieving lower emission targets? The case of Sweden. Transp. Policy 142, 125–136. https://doi.org/10.1016/j.tranpol.2023.08.013.

Box, G.E.P., Jenkins, G.M., Reinsel, G.C., 2008. Time Series Analysis. Wiley. https://doi.org/10.1002/9781118619193.

Bruinsma, F., Koster, P., Holtmann, B., van Heumen, E., Beuthe, M., Urbain, N., Jourquin, B., Ubbels, B., & Quispel, M. (2012). *Consequences of Climate Change for Inland Waterway Transport, Deliverable 3.3 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport.*

CCNR. (2022a). *An assessment of new market opportunities for Inland Waterway Transport*. https://inland-navigation-market.org/wp-content/uploads/2022/03/Thematic-report_20212022_EN_BD.pdf.

CCNR. (2021). *Act now!" on low water and effects on Rhine navigation*. https://www.ccr-zkr.org/files/documents/workshops/wrshp261119/ien20_06en.pdf.

CCNR. (2022b). *Annual Report*. https://inland-navigation-market.org/wp-content/uploads/2022/10/CCNR_annual_report_EN_2022_BD.pdf.

Christodoulou, A., Christidis, P., Bisselink, B., 2020. Forecasting the impacts of climate change on inland waterways. Transp. Res. Part D: Transp. Environ. 82, 102159 https://doi.org/10.1016/j.trd.2019.10.012.

Commission, E., 2011. Transport White Paper. Roadmap to a Single European Transport Area - towards a Competitive and Resource Efficient Transport System. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:EN:PDF.

European Commission. (2017). *Study on the TEN-T Core Network Corridor Rhine-Alpine*. https://transport.ec.europa.eu/system/files/2022-02/ralp_corridor_final_report_2017.pdf.

European Commission. (2019). *Handbook on the external costs of transport*. https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1.

COVADEM. (2023). *Smart navigation, smart dashboard, smart performance*. https://www.covadem.com/en/home/.

Deltares. (2023). *Implications of the KNMI'23 climate scenarios for the discharge of the Rhine and Meuse*. https://open.rijkswaterstaat.nl/publish/pages/193035/implications_of_the_knmi23_climate_scenarios_for_the_rhine_and_meuse.pdf.

ECA. (2015). *Inland Waterway Transport in Europe: No significant improvements in modal share and navigability conditions since 2001*. https://www.eca.europa.eu/Lists/ECADocuments/SR15_01/SR15_01_EN.pdf.

UTP Erasmus. (2020). *Economische impact laagwater*. https://bo-blns.websteks.nl/uploads/images/Erasmus%20UPT%20-%20Eindrapport%20Economische%20impact%20laagwater.pdf.

EURIS. (2024). *Fairways based on CEMT class*. https://www.eurisportal.eu/waterway/cemtmap.

European IWT Platform. (2022). *Annual Report 2022*. https://www.inlandwaterwaytransport.eu/wp-content/uploads/IWT-Annual-Report-2022.pdf.

Eurostat, 2022. Inland waterway transport statistics. Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Inland_waterway_transport_statistics.

Eurostat, 2023a. Inland waterways - statistics on container transport. Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Inland_waterways_-_statistics_on_container_transport.

Eurostat. (2023b). *Modal split of inland freight transport*. https://ec.europa.eu/eurostat/databrowser/view/TRAN_HV_FRMOD__custom_6044915/default/table?lang=en.

Hamilton, J.D., 1994. Time Series Analysis. Princeton University Press, Princeton, NJ.

INE. (2016). *Inland Waterway Transport by Numbers*. https://www.inlandnavigation.eu/wp-content/uploads/2021/04/IWT_by_numbers_2016.pdf.

Jonkeren, O., Rietveld, P., van Ommeren, J., 2007. Climate Change and Inland Waterway Transport: Welfare Effects of Low Water Levels on the River Rhine. JTEP 41 (3), 387–411. https://www.jstor.org/stable/20054027.

Jonkeren, O., Jourquin, B., Rietveld, P., 2011. Modal-split effects of climate change: The effect of low water levels on the competitive position of inland waterway transport in the river Rhine area. Transp. Res. A Policy Pract. 45 (10), 1007–1019. https://doi.org/10.1016/j.tra.2009.01.004.

Jonkeren, O., Rietveld, P., van Ommeren, J., te Linde, A., 2014. Climate change and economic consequences for inland waterway transport in Europe. Reg. Environ. Chang. https://doi.org/10.1007/s10113-013-0441-7.

Kendra, M., Skrúcaný, T., Dolinayová, A., Čamaj, J., Jurkovič, M., Csonka, B., Abramović, B., 2023. Environmental burden of different transport modes – Real case study in Slovakia. Transp. Res. Part D: Transp. Environ. 114, 103552 https://doi.org/10.1016/j.trd.2022.103552.

KNMI. (2023). *KNMI'23-klimaatscenario's*. Ministerie van Infrastructuur En Waterstaat. https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s.

Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: An overview of empirical findings. Transportation Research Part D: Transport and Environment 14 (3), 205–221. https://doi.org/10.1016/j.trd.2008.12.004.

Linde, T.e., 2007. Effect of climate change on the rivers Rhine and Meuse. In WL Delft Hydraulics, Prepared for Rijkswaterstaat.

Michaelides, S., Leviäkangas, P., Doll, C., Heyndrickx, C., 2014. Foreward: EU-funded projects on extreme and high-impact weather challenging European transport systems. Nat. Hazards 72 (1), 5–22. https://doi.org/10.1007/s11069-013-1007-1.

Millerd, F., 2005. The Economic Impact of Climate Change on Canadian Commercial Navigation on the Great Lake. Canadian Water Resources Journal 30 (4), 269–280. https://doi.org/10.4296/cwrj3004269.

Novimove. (2023). *Solving inefficiencies on the IWT Rhine-Alpine corridor*. Novel Inland Waterway Transport Concepts for Moving Freight Effectively. https://novimove.eu/?cn-reloaded=1.

Olsen, J.R., Zepp, L.J., Dager, C.A., 2005. Climate Impacts on Inland Navigation. Impacts of Global Climate Change 1–8. https://doi.org/10.1061/40792(173)463.

European Parliament. (2022). *Inland waterway transport in the EU*. Think Tank. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698918#:~:text=Inland%20waterway%20transport%20(IWT)%20is,and%2050%20%25%20of%20rail%20transport.

Rijkswaterstaat. (2023). *Future discharges in the Rhine and Meuse: lower in summer and higher in winter*. Future Discharges in the Rhine and Meuse: Lower in Summer and Higher in Winter. https://www.rijkswaterstaat.nl/en/news/archive/2023/12/future-discharges-in-the-rhine-and-meuse-lower-in-summer-and-higher-in-winter.

Schweighofer, J., Gebraad, J., & Seitz, M. (2022). *Options for shallow-water/climate resilient vessels*. platina3.eu/options-for-shallow-water-climate-resilient-vessels/.

Schweighofer, J., Nilson, N., Klein, B., Lingemann, I., Krahe, P., Baling, G., Gnandt, B., Horanyi, A., Szepszo, G., 2012. Impact of climate change on hydrological conditions of navigation. ECCONET deliverable 1, 5. http://www.ecconet.eu/deliverables/index.htm.

Shobayo, P., & van Hassel, E. (2019). Container barge congestion and handling in large seaports: a theoretical agent-based modeling approach. *Journal of Shipping and Trade 2019 4:1*, *4*(1), 1–26. DOI: 10.1186/S41072-019-0044-7.

Van Meir, N., Rashed, Y., Storms, K., Sys, C., Vanelslander, T., Van Hassel, E., 2022. The future container throughput for inland shipping on the traditional Rhine: a SARIMAX approach. Eur. J. Transp. Infrastruct. Res. 22 (4) https://doi.org/10.18757/ejtir.2022.22.4.6552.

Vinke, F., van Koningsveld, M., van Dorsser, C., Baart, F., van Gelder, P., Vellinga, T., 2022. Cascading effects of sustained low water on inland shipping. Clim. Risk Manag. 35, 100400 https://doi.org/10.1016/j.crm.2022.100400.