The Role of Transfer Hubs in Climate-Resilient Porthinterland Connections
Implications for Port Competition

Pourmohammad-Zia, Nadia; van der Plas, Luuk; van Koningsveld, Mark

Publication date
2025

Document Version
Final published version

Citation (APA)
Pourmohammad-Zia, N., van der Plas, L., & van Koningsveld, M. (2025). *The Role of Transfer Hubs in Climate-Resilient Porthinterland Connections: Implications for Port Competition* . 1992-1999. Paper presented at IAME 2025 Conference, Bergen, Norway.

THE ROLE OF TRANSFER HUBS IN CLIMATE-RESILIENT PORT-HINTERLAND CONNECTIONS: IMPLICATIONS FOR PORT COMPETITION

Nadia Pourmohammad-Zia[1*], Luuk van der Plas[1], Mark van Koningsveld[1,2]

[1]Department of Hydraulic Engineering, Delft University of Technology, The Netherlands

[2]Van Oord Dredging and Marine Contractors, 3068 NH Rotterdam, The Netherlands

(*n.pourmohammadzia@tudelft.nl)

Abstract

The increasing frequency of extreme weather events poses significant challenges to inland waterway transport, a vital mode of port-hinterland connectivity in Europe. Low water levels disrupt vessel operations by reducing their transport capacity. This study investigates the potential of transfer hubs along the Rhine-Alpine corridor to address this challenge and maintain efficient cargo flows during drought conditions. It offers a replicable methodology for evaluating hub placement and transport resilience, incorporating multi-criteria decision-making and transport modeling. Using a transport competition model, three scenarios, including baseline, drought, and transfer hub application, are simulated to evaluate the cost-effectiveness of implementing these hubs at strategic locations. The integration of hubs, particularly near Duisburg and Andernach, demonstrated the potential to sustain 80% operability during disruptions by enabling modal shifts and alleviating bottlenecks. While competition in the North-Western European hinterland, involving ports such as the Port of Rotterdam, Hamburg, and Antwerp, is further intensified by climate-induced disruptions, our results show that transfer hubs can help ports secure their competitive advantages by ensuring reliable cargo flow under adverse conditions. Our findings highlight the strategic importance of transfer hubs in mitigating climate impacts, enhancing port competition, and supporting sustainable hinterland logistics.

Keywords

Climate Resilience, Port-Hinterland, Transfer Hubs, Port Competition, Drought

1 Introduction

The increasing frequency of extreme weather events presents significant challenges to inland waterway transport (IWT), a key mode of hinterland connectivity in Europe. Climate change-induced fluctuations in water levels disrupt vessel operations, reducing cargo capacity and increasing transport costs. In particular, the Rhine-Alpine corridor, a major route for freight transport from the Port of Rotterdam (PoR), faces recurrent disruptions due to prolonged droughts (Jonkeren and Rietveld, 2009). These disruptions not only weaken the reliability of IWT but also threaten its competitive position relative to road and rail transport. With the European Commission aiming to shift more freight towards sustainable modalities, ensuring the resilience of IWT against climate-related challenges is essential (European Commission, 2021).

Periods of drought, such as those experienced in 2018 and 2022, have demonstrated the vulnerability of inland shipping (Fechner and Luman, 2023). Low water levels force vessels to operate with reduced loads, increasing the number of trips required and intensifying congestion at ports and along waterways. This inefficiency leads to higher transport costs and a decline in IWT's share of hinterland freight transport. At the same time, competition among major seaports in North-Western Europe, Rotterdam, Hamburg, and Antwerp, intensifies as cargo owners seek reliable and cost-effective transport alternatives. Existing studies have identified vessel modifications, waterway adjustments, and improved scheduling as potential mitigation strategies in this respect (Friedhoff, 2020; Gobert and Rudolf, 2023). However, limited research has explored the role of modal shift in addressing climate-induced disruptions, despite their potential to alleviate transport bottlenecks and enhance resilience.

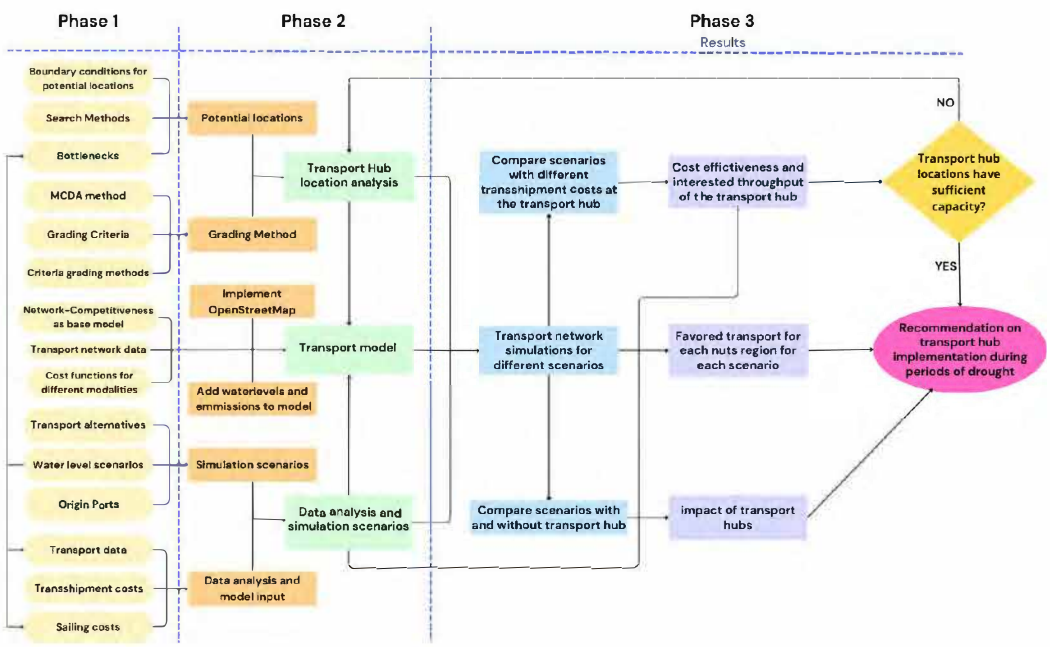
A key solution to facilitate modal shift lies in the implementation of intermodal transfer hubs at strategic locations along the Rhine. These hubs would facilitate modal shifts from IWT to rail or road when water levels are too low for efficient navigation, thereby mitigating transport disruptions and maintaining the competitiveness of IWT. While previous research has explored vessel and waterway modifications to address low-water challenges, limited studies have investigated the role of transfer hubs in enhancing transport resilience (Riquelme-Solar et al., 2015). This research aims to bridge that gap by assessing the cost-effectiveness of transfer hubs as a means to sustain hinterland connectivity and port competitiveness during periods of drought.

The study develops a transport competition model to quantify the impact of transfer hubs on port-hinterland resilience. The model simulates different scenarios, including baseline, drought, and transfer hub integration, to evaluate their effectiveness in maintaining cargo flows. Key objectives include identifying critical bottlenecks along the Rhine, assessing the optimal locations for transfer hubs, and determining their influence on transport costs and port competition. By providing a replicable methodology for evaluating transfer hubs, this research offers practical insights for policymakers and industry stakeholders aiming to strengthen European freight transport networks against climate-induced disruptions.

2 Methodology

This study employs a multi-phase methodology to assess the impact of transfer hubs on port-hinterland resilience during drought conditions. The research follows a structured approach comprising bottleneck identification, data analysis, location analysis for transfer hubs, and transport competition modeling. Figure 1 provides an overview of the methodology and its interconnected components.

Figure 1
Overview of the methodology framework



2.1 Bottleneck Identification

The first step of our methodology involves identifying critical bottlenecks along the Rhine corridor by analyzing historical data from the 2018 and 2022 droughts. Water depth data, transport delays, and cost surcharges at key locations such as Kaub, Nijmegen, and Duisburg are assessed to determine their impact on IWT. A rule-based calculation method is used to estimate sailing depths at different locations to identify bottlenecks effectively. This step provides the basis for evaluating the necessity of transfer hubs and understanding the economic impact of low water levels on hinterland connectivity.

2.2 Data Collection and Analysis

Data from Rijkswaterstaat, the PoR, and historical transport records are analyzed to quantify cargo throughput reductions during drought periods. Vessel fleet compositions, water levels, and cost variations are examined to estimate the cargo volume requiring modal shifts for maintaining network operability. Water level scenarios are classified into baseline and drought conditions, ensuring that the model accurately reflects real-world disruptions.

2.3 Transfer Hub Location Analysis

Potential hub locations near identified bottlenecks are evaluated using a Multi-Criteria Decision-Making approach, specifically the Best-Worst Method. Factors such as infrastructure availability, multimodal accessibility, and cost efficiency are weighted based on expert input from the PoR and TU Delft. The analysis helps identify optimal locations for integrating transfer hubs to mitigate transport disruptions caused by low water levels.

2.4 Transport Competition Model

A Python-based transport model is developed to simulate port-hinterland competition among Rotterdam, Hamburg, and Antwerp under different scenarios: baseline, drought, and drought with transfer hubs. The model builds upon an earlier network-competitiveness model by de Iongh (2020) and incorporates shortest-route algorithms, cost functions for rail, road, and IWT, and water level data to estimate modal shifts and cost-effectiveness. The integration of transfer hubs allows the model to assess their potential in mitigating transport disruptions and improving port competitiveness. The model also utilizes NUTS regions as hinterland destinations, aligning with Eurostat classifications to ensure consistency in regional economic analysis. Different water levels are incorporated into the model, affecting vessel capacity and modal choices, thereby influencing port-hinterland competition. The transport cost calculations consider transshipment costs, infrastructure fees, and emissions, providing a holistic assessment of the economic and environmental impact of transfer hubs.

By combining these methodological components, the study develops an integrated framework to assess the feasibility and cost-effectiveness of transfer hubs in enhancing port-hinterland resilience. The results of the simulations and analyses will inform strategic recommendations for improving IWT sustainability and competitiveness.

3 Results

This section presents the key findings from the transport competition model, analyzing the effects of low water levels on IWT and assessing the potential of transfer hubs in mitigating disruptions. The results are structured around the baseline scenario, the drought scenario, and the drought scenario with transfer hubs integrated. Additionally, the location analysis for transfer hubs is summarized to provide context for the simulations.

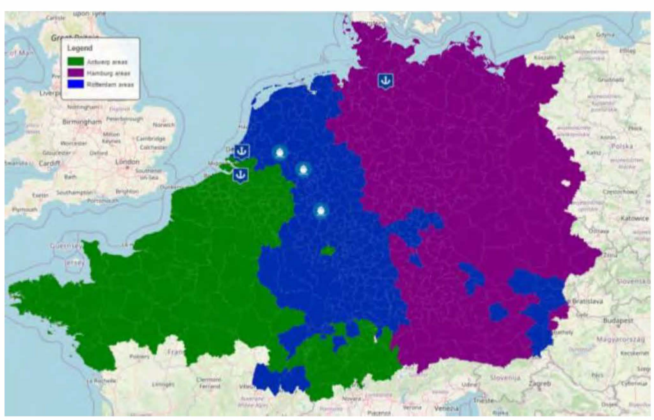
3.1 Transfer Hub Location Analysis

The location analysis identified Nijmegen, Duisburg, and Andernach (near Kaub) as optimal sites for transfer hubs based on infrastructure availability, accessibility, and cost-effectiveness. The Duisburg Gateway Terminal emerged as the highest-rated location, benefiting from strong multimodal connectivity. The analysis showed that a medium-sized hub in Andernach (193,725 TEU/year) would be crucial for maintaining network operability past Kaub, while a smaller hub in Nijmegen (14,700 TEU/year) would contribute to overall system resilience.

3.2 Baseline Scenario

The baseline scenario simulated normal operating conditions for the inland waterway network. The model identified 259 NUTS regions where PoR was the most cost-effective seaport for hinterland transport, compared to 117 for Antwerp and 248 for Hamburg. IWT was the dominant transport mode for PoR's hinterland, with rail transport playing a stronger role for Hamburg and Antwerp. The cost analysis (Figure 2) indicated that Rotterdam maintained a competitive edge in regions along the Rhine and Moesel waterways but faced close competition with Antwerp for more distant hinterland locations.

Figure 2
Baseline Scenario Results



3.3 Drought Scenario

During drought periods, the model showed a significant reduction in Rotterdam's competitive hinterland regions. The number of NUTS regions where Rotterdam was the most cost-effective option dropped by 59%, reducing its dominance to 106 regions (Figure 3). Antwerp and Hamburg gained a substantial share due to their stronger reliance on rail transport, which remained unaffected by water level fluctuations. The most affected areas were those past Kaub, where the cost of IWT increased sharply due to reduced vessel loading capacities (Figure 4). The loss of hinterland access highlights the vulnerability of IWT during climate-induced disruptions.

Figure 3
Drought Scenario Results

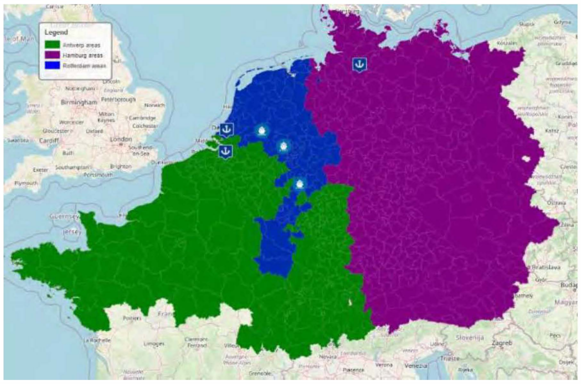
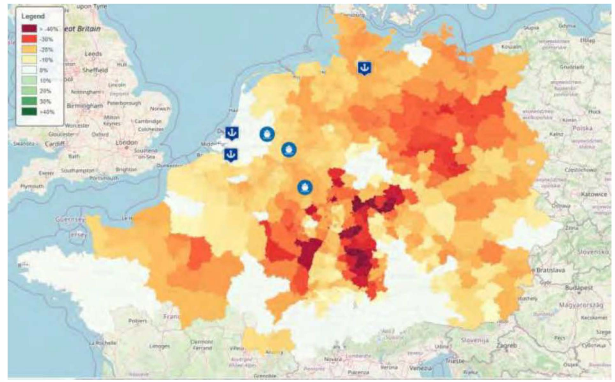


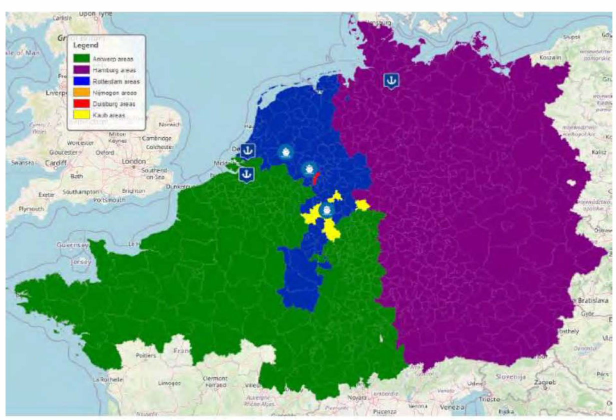
Figure 4
Transport Price Increase (%) from PoR during Drought



3.4 Drought Scenario with Transfer Hubs

The introduction of transfer hubs was evaluated for its potential to mitigate the adverse effects of drought conditions. The analysis showed that hubs could provide cost savings if transshipment costs were kept at or below €50 per TEU. Among the three proposed locations, the hub at Kaub proved most effective in maintaining IWT's competitive position. While hubs in Nijmegen and Duisburg offered advantages for shifting cargo to rail, they had a limited effect on overall transport costs (Figure 5).

Figure 5
Drought with Transfer Hubs Scenario Results with €50 per TEU Transshipment Costs



3.5 Discussion

The results highlight the substantial impact of drought periods on the competitiveness of IWT and the effectiveness of transfer hubs in mitigating disruptions. The competitive dynamics among seaports reveal that Rotterdam's reliance on IWT makes it particularly vulnerable to climate-related disruptions. The model's predictions closely align with historical patterns observed in the 2018 and 2022 droughts, reinforcing the validity of the approach.

A key finding from the transport competition model is that the effectiveness of transfer hubs is highly sensitive to transshipment costs. It also depends on the hub's location, where the hub before bottleneck Kaub proved to be most effective. Transport hub Nijmegen is effective as a sustainable solution, and Duisburg is effective for transshipment towards rail. This suggests that targeted subsidies or operational efficiencies are necessary to make hubs a practical solution during droughts. While the hubs provide a means of reducing transport costs, their long-term viability depends on policy interventions and investments in multimodal logistics.

The results also underscore the importance of strategic planning for inland terminal capacity. The study suggests that medium-sized hubs in Duisburg and Andernach, each handling approximately 130,000 TEU/year, would be optimal. Nijmegen, while less effective for container transport, could still serve as a sustainable logistics hub by facilitating modal shifts to rail. The data analysis showed that 43% of baseline cargo transport must be relocated to alternative modes to maintain 80% network operability. This confirms the necessity of integrating transfer hubs with other resilience measures, such as vessel fleet adaptations and optimized scheduling.

Finally, the study acknowledges limitations related to data availability and modeling assumptions. The uniformity of cost calculations across seaports and the exclusion of certain factors, such as port congestion and real-time delays, may introduce minor inaccuracies. However, the overall findings provide strong evidence supporting the role of transfer hubs in enhancing the resilience of port-hinterland connections against climate-induced disruptions.

Aknowledgement

Funded by the European Union. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the Horizon Europe research and innovation programme. Neither the European Union nor the granting authority can be held responsible for them.

References

Anku, R., Pruyn, J., & Thill, C. (2024, May). A review of the state-of-the-art Sustainable and Climate-resilient inland waterway vessels. In International Marine Design Conference.

de Iongh, Z. (2020). The impact of high sea-level rise (1-5 m) on mainport hinterland transport networks: A method for assessing adaptive sea-level rise scenarios on container port competition; a case study for the port of Rotterdam.

European Commission. (2021). Inland Waterways European Commission, Available at: https://transport.ec.europa.eu/transport-modes/inland-waterways_en

Fechner, I., & Luman, R. (2023, October). Extreme weather is making major trade routes less reliable, and it's only going to get worse. https://think.ing.com/articles/extreme-weather-makesmajor-trade-routes-less-reliable/#a1

Gobert, J., & Rudolf, F. (2023). Rhine low water crisis: from individual adaptation possibilities to strategical pathways. Frontiers in Climate, 4, 1045466.

Jonkeren, O., & Rietveld, P. (2009). Impacts of low and high water levels on inland waterway transport, literature review for 'kennis voor klimaat'.

Riquelme-Solar, M., Van Slobbe, E., & Werners, S. E. (2015). Adaptation turning points on inland waterway transport in the Rhine River. Journal of Water and Climate Change, 6(4), 670-682.