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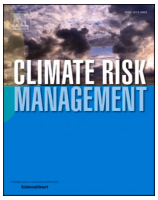

# Inland shipping response to discharge extremes – A 10 years case study of the Rhine

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ABSTRACT

Inland shipping is a key modality for freight transport between the seaport of Rotterdam and the industrial areas in Germany and Switzerland. The recent droughts of 2018, 2019 and 2022 have clearly demonstrated how discharge related supply chain disruptions cause substantial economic damages in the hinterland. The IPCC predicts that climate change will increase the variability in water cycles globally, making future extremes more frequent and more severe. In-depth insight into the response of inland shipping to discharge extremes is crucial to better anticipate and potentially mitigate this climate risk. Existing literature takes (a small number of) representative vessels and estimates corridor scale climate risks through extrapolation. Recent droughts have shown that this approach may give unrealistic results. Newspaper articles and reports from the sector suggest that the fleet composition and vessel deployment change during high and low discharge extremes, and cascading effects are likely to occur. So far, however, no objective data on this phenomenon has been reported in literature. This paper analyses ten years of IVS and discharge data, for the period between 2010 and 2020, revealing in detail for the first time how discharge levels and vessel deployment are related. This improved insight into shipping response is crucial for any corridor to accurately estimate the climate risk of discharge extremes. While this paper focuses on the Rhine corridor, the proposed method is applicable to other corridors as well.

## 1. Introduction

The Port of Rotterdam is Europe's largest port. In 2021, it handled 468.7 million tonnes of cargo (Port of Rotterdam, 2021a; Port of Rotterdam, 2021b). An extensive network of high-quality hinterland connections, viz. roads, rail, pipelines and waterways, has contributed significantly to this position. It allowed shipping companies and carriers to develop multiple logistic services for cargo transport into the hinterland.

The river Rhine is a key asset in Rotterdam's network of hinterland connections and the seaports of Antwerp, North Sea Ports and Amsterdam. It connects six large industrial clusters (from West to East): Rotterdam-Europoort, Metropolitan region Rhine-Ruhr, Frankfurt-Rhine-Main, Rhine-Neckar, Strasbourg, and Basel/Mulhouse/Freiburg. Multiple vessel classes are used to transport a

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**Table 1**
Results current literature.

| Year | Reference | Discharge $m^3/s$ | Vessels | Cargo |
|---|---|---|---|---|
| **2013** | (Verschuren, 2020) | 700, 800, 900, 1020 | BII-4, −2 l & −1 and C2l | |
| | (Wienk, 2021) | 700, 850, 1020 and 2500 | BII-4, C3l & C4, M8, M9, M10 | dry bulk & liquid bulk |
| **2014** | (Van Dorsser et al., 2020) | | | dry, liquid & containers |
| | (Van der Wijk and De Jong, 2021) | thresholds: 5.580 & 11.454 | | containers |
| **2015** | (Verschuren, 2020) | 700, 800, 900, 1020 | BII-4, −2 l & −1 and C2l | |
| **2018** | (Kievits, 2019) | waterdepths 3.0 and 2.25 m | BII-6,4,2, coupled units | dry bulk |
| | (De Jong, 2020a) | 500–3500, thresholds: 1700 & 2000 | | dry & liquid bulk |
| | (Verschuren, 2020) | 700, 800, 900, 1020 | BII-4, −2 l & −1 and C2l | |
| | (Wienk, 2021) | 700, 850, 1020 & 2500 | BII-4, C3l & C4, M8, M9, M10 | dry bulk & liquid bulk |
| **2019** | (Ligtenberg, 2022) | threshold: 2000 | | |

range of different cargo types (i.e. dry bulk, liquid bulk and containers).

Achieving economies of scale has been a key driver to increase the dimensions of inland ships on the Rhine for the past decades (Groen and Van Meijeren, 2010; Quist et al., 2011; Hekkenberg, 2013). On the one hand this promoted Inland Water Transport (IWT) as an economically attractive transport mode. On the other hand it made IWT more vulnerable to discharges extremes (Kriedel et al., 2019; De Jong, 2020b).

The 2018, 2019 and 2022 low-discharge extremes clearly demonstrated the Rhine's current vulnerability to droughts. Kriedel et al. (2019) and Prognose (2022) show that droughts, as well as floods, have led to substantial supply chain disruptions and consequent economic impacts. The Intergovernmental Panel on Climate Change (IPCC) predicts that extreme river discharges (high or low), will become more frequent and more severe as climate change progresses. This will adversely affect the water transport performance of the Rhine (De Jong, 2020b; Van der Wijk and De Jong, 2021), and likely other inland shipping networks world wide.

Vinke et al., 2022 show how vessels, and the supply chains they participate in, are affected by changing discharges. At an operational/short term level, barge operators need to decide how many vessels of which class they need to deploy where, and how much cargo can be loaded in light of (air) draught bottlenecks along the anticipated route.

Along the Rhine, vessels need to pass a number of critical areas which are well-known by barge operators. Examples are Nijmegen, Ruhrort and Kaub which determine the maximum loading capacities of the vessels that have to pass these locations. Dry bulk is mainly transported to inland ports near Duisburg and only pass bottlenecks Nijmegen and Ruhrort. A part of the liquid bulk and containers are transported further upstream and will pass Kaub; the main bottleneck between Duisburg and Basel.

At a strategic/medium-long term level, shipping companies need to consider to what extent they should modify their fleet composition in order to promote resilience to changing climate conditions. Insight into how inland shipping responds to discharge extremes is essential for both. This phenomenon to date has received little to no attention in open literature.

Earlier publications typically selected (a small number of) representative vessels and estimated corridor-scale climate risks through extrapolation (e.g. Jonkeren et al., 2014; Van Dorsser, 2015; Christodoulou et al., 2020). Recent droughts have shown that this approach may give unrealistic results. Newspaper articles (Van 't Verlaat, 2019; Sterling, 2022; Gross, 2022; Oltermann, 2022; Schneeweiss, 2022; Reuters, 2022) and reports (Jonkeren and Rietveld, 2009; Schweighofer, 2014; Nur et al., 2020) mention that multiple vessels are deployed or discuss the vulnerability of individual vessel classes. This suggests that the fleet composition and vessel deployment change during high and low extremes.

More recent studies looked into vessel deployment and fleet composition for various discharges on the most important Rhine branch in the Netherlands: the Waal (Kievits, 2019; Van Dorsser et al., 2020; De Jong, 2020a; Verschuren, 2020; Wienk, 2021; Van der Wijk and De Jong, 2021; Ligtenberg, 2022). The main objective of these studies was to derive a representative fleet mixture and vessel deployment based on Informatie- en VolgSysteem voor de Scheepvaart (IVS) data for impact assessments or design of infrastructural measures. Table 1 summarises the main conclusions from these studies. It shows (1) an emphasis on lower discharges, (2) a limited number of analysis years, and (3) a relatively small sub-selection of the passing vessel classes.

A comprehensive overview of the fleet composition and vessel deployment for a wide range of discharge conditions, an extended time period, a wide range of discharge conditions and for the complete list of passing vessel classes is lacking in current literature. The objective of this paper, therefore, is to analyse the fleet composition and vessel deployment for a wide range of discharge conditions, for a ten-year period (2010–2019), based on detailed IVS data (vessel classes, loading rates, etc) and daily averaged discharge data for the Dutch part of the Rhine, in order to examine the shipping behaviour for a series of discharge conditions that can be used in logistic simulation packages that have an agent-based approach to estimate the climate risk on inland shipping more accurately during discharge extremes.

Section 2 describes the data and the methodology to analyse the datasets. Section 3 presents the results of the analysis, followed by a discussion in Section 4. Finally we state our conclusions and recommendations in Section 5.

## 2. Materials and methods

### 2.1. Data

To assess vessel deployment under varying river discharges, we combine daily-averaged discharge data (obtained from:

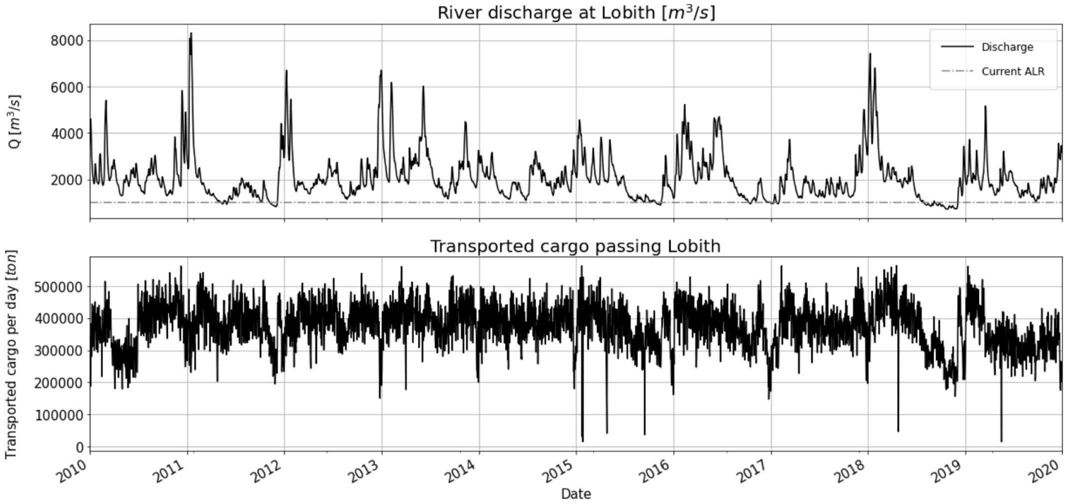


**Fig. 1.** Daily averaged discharges at Lobith for the period from 2010 to 2020.

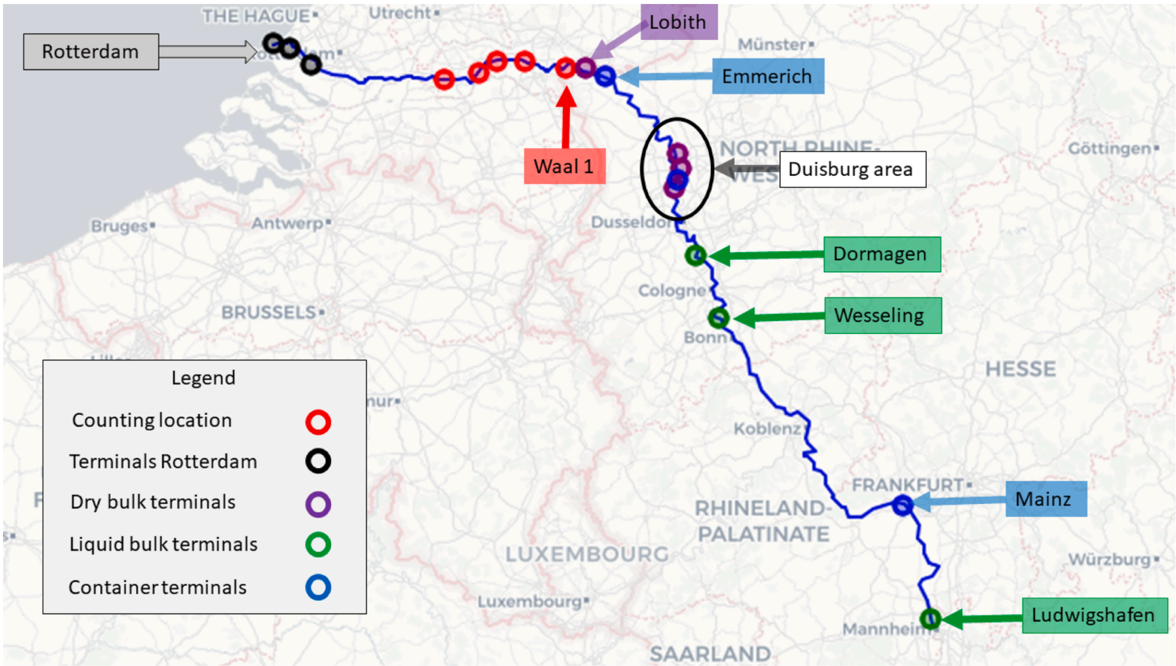


**Fig. 2.** Overview of the terminals in the port of Rotterdam, the IVS-counting locations on the Waal, the gauge station at Lobith and the terminals in Germany.

Rijkswaterstaat, 2022) with IVS data (obtained from: Rijksoverheid, 2022) at Lobith for the period 2010–2020.

To support the values and interests on the Dutch waterways Rijkswaterstaat routinely collects discharge data at several locations. The daily averaged discharges at Lobith, the place where the Rhine enters the Netherlands, are shown in Fig. 1 for the period between 2010 and 2020. The dashed dotted line represents the Agreed Low River discharge (ALR) of 1020 $m^3/s$ for which a minimum navigable depth of 2.80 m should be available (Central Commision for the navigation of the Rhine, 2020).

In the Netherlands vessel transport data and trip information are recorded with several methods. The two main methods are Automatic Identification System (AIS) data and IVS data. AIS data are part of an automatic tracking system that uses transceivers on ships. Their main purpose is for live use in Vessel Traffic Services (VTSs) but recorded AIS data can be useful to analyse vessel trajectories and speeds to assess and improve waterway capacity and safety. IVS data record a range of physical properties of the vessel, viz. length, beam, draught, vessel class and information about the trip that is executed, including origin, destination and cargo (i.e. transported cargo amount or number of containers). The classification of the vessels in the IVS data is based on Rijkswaterstaat

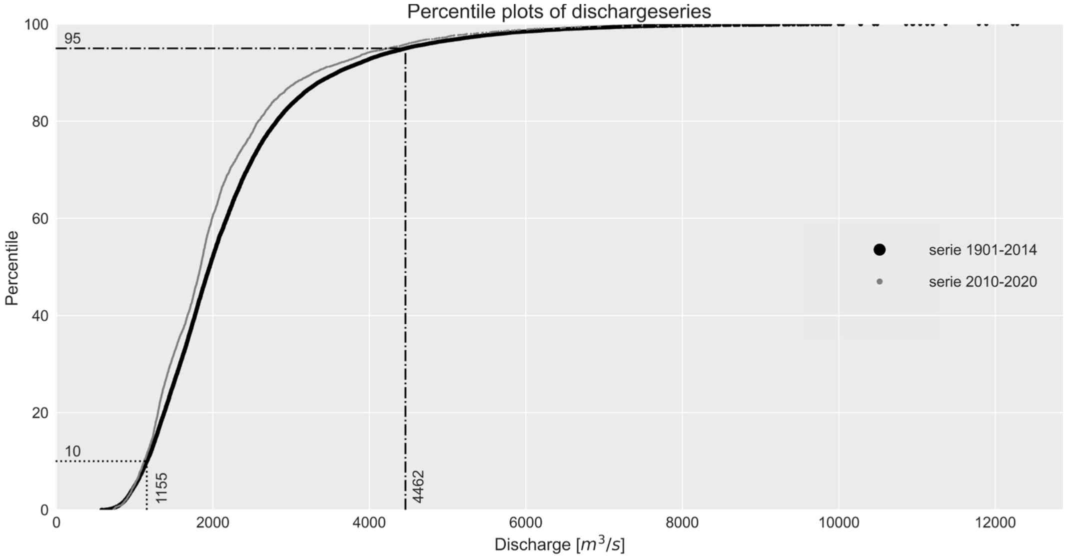


**Fig. 3.** Percentiles of discharges.

definitions (Koedijk et al., 2020). An overview of the classification and the corresponding vessel properties is given in Table 2 in the appendix.

IVS data is measured at multiple counting locations along the IWT network. Fig. 2 gives a schematic overview of the five counting locations at the river Waal. The counting locations represent the traffic along the following trajectories:

- Waal 1 Germany – Maas-Waal canal,
- Waal 2 Maas-Waal canal – Druten,
- Waal 3 Druten – Tiel,
- Waal 4 Tiel – St. Andries,
- Waal 5 St. Andries – Boven Merwede

For the analysis in this paper we used the data of counting location Waal 1. This dataset includes all the vessels that pass Lobith with a origin or destination in the Netherlands or Germany. For our analysis, however, we only included vessels that navigate between Rotterdam and the top three inland ports in Germany for cargo types: dry bulk, liquid bulk and containers. We consider the following indicators: number of trips, transported volume, transported containers (TEU), and average vessel loading rates.

### *2.2. Data-analysis*

To examine fleet composition and vessel deployment for varying river discharges we define distinct discharge bins for which we will analyse the pre-mentioned indicators.

For an objective selection of bin boundaries a statistical analysis of discharge percentile values was performed on 113 years (1901–2014) of discharge records provided by Rijkswaterstaat, Fig. 3. NB: It should be noted that the analysis is based on the ‘daily-averaged discharge values’ rather than the ‘yearly maximum values’ that are commonly used in flood-risk assessments.

Based on this analysis we define events below the 10-percentile (1155 $m^3/s$) as ‘low discharge’ events and events above the 95-percentile (4462 $m^3/s$) ‘high discharge’ events. The 10-percentile value is just above the ALR (1020 $m^3/s$) and the lower limit for six-barge push-tow units (1086 $m^3/s$)(Ministry of Transport, 2018), while the 95-percentile is just below the value (5580 $m^3/s$) for which the head clearance of bridges that cross the Waal becomes insufficient, as determined by Van der Wijk and De Jong (2021). For practical purposes we round both values up to hundreds, 1200 and 4500 respectively, and use these values to distribute bins over the total range of discharges.

In the 2010–2020 dataset of Lobith discharges (Fig. 2) the smallest daily averaged discharge value is 726 $m^3/s$ (measured in 2018) while the maximum value is 8374 $m^3/s$ (measured in 2011). The total range of the discharge bins will therefore be specified between 700 and 8500 $m^3/s$ so all the observations in the dataset are included. For the low discharges (700–1200 $m^3/s$) we select a bin size of 50 $m^3/s$ which represents a water level difference of 10 cm at Lobith (Rijkswaterstaat, 2019). Based on a rule of thumb a 10 cm water level difference in the low discharge range corresponds with a 100 ton reduction in vessel loading capacity. For the high discharges (4500–8500 $m^3/s$) we select a bin size of 250 $m^3/s$, which corresponds to a water level difference of 20 cm at Lobith (Rijkswaterstaat, 2019). We have chosen to use a larger bin size for the high discharges because the number of observations reduces towards the higher extreme. For the regular discharges (1200–4500 $m^3/s$) we select a bin size of 500 $m^3/s$ for normal navigable conditions. This results in six 500 $m^3/s$ bins between 1500–4500 $m^3/s$ and one 300 $m^3/s$ bin between 1200–1500 $m^3/s$ to complete the total range. Within the regular discharge range no specific shipping behaviour is expected based on current literature (Ligtenberg, 2022).

For each of the discharge bins we identify the corresponding discharge events in the discharge records and match these with the IVS data to quantify the following indicators: 1) number of trips, 2) transported volume and 3) transported containers (TEU) and 4) average vessel loading rates, each as a function of the daily averaged discharge. The indicators are quantified using the following equations.

The totals for the number of trips, the transported volume and the transported containers are calculated by summing the number of observations in a bin:

$$\mathrm{trips}_{\mathrm{totalperbin}} = \sum^{n} trips \tag{1}$$

$$\mathrm{TransportedVolume}_{\mathrm{totalperbin}} = \sum^{n} \mathrm{TransportedVolume} \tag{2}$$

$$\mathrm{Containers}_{\mathrm{totalperbin}} = \sum^{n} Containers \tag{3}$$

In which:

$n$ number of observations per bin

Since the number of trips changes with varying discharges we also calculate the average values of the transported volume and transported containers per day and per trip in a bin:

$$\mathrm{Trips}_{\mathrm{averagedperday}} = \frac{\mathrm{Trips}_{\mathrm{totalperbin}}}{days_{\mathrm{perbin}}} \tag{4}$$

$$\mathrm{Transportedvolume}_{\mathrm{averagedperday}} = \frac{\mathrm{Transportedvolume}_{\mathrm{totalperbin}}}{days_{\mathrm{perbin}}} \tag{5}$$

$$\mathrm{Containers}_{\mathrm{averagedperday}} = \frac{\mathrm{Containers}_{\mathrm{totalperbin}}}{days_{\mathrm{perbin}}} \tag{6}$$

$$\mathrm{Transportedvolume}_{\mathrm{averagedpertrip}} = \frac{\mathrm{Transportedvolume}_{\mathrm{totalperbin}}}{trips_{\mathrm{perbin}}} \tag{7}$$

$$\mathrm{Containers}_{\mathrm{averagedpertrip}} = \frac{\mathrm{Containers}_{\mathrm{totalperbin}}}{trips_{\mathrm{perbin}}} \tag{8}$$

Most of the figures in Section 3 consist of three panels. The order of these panels is:

- upper panel: total transported cargo and containers per day according Eq. 5 and Eq. 6;
- middle panel: number of trips Eq. 4;
- lower panel: transported cargo and containers per trip according Eq. 7 and Eq. 8.

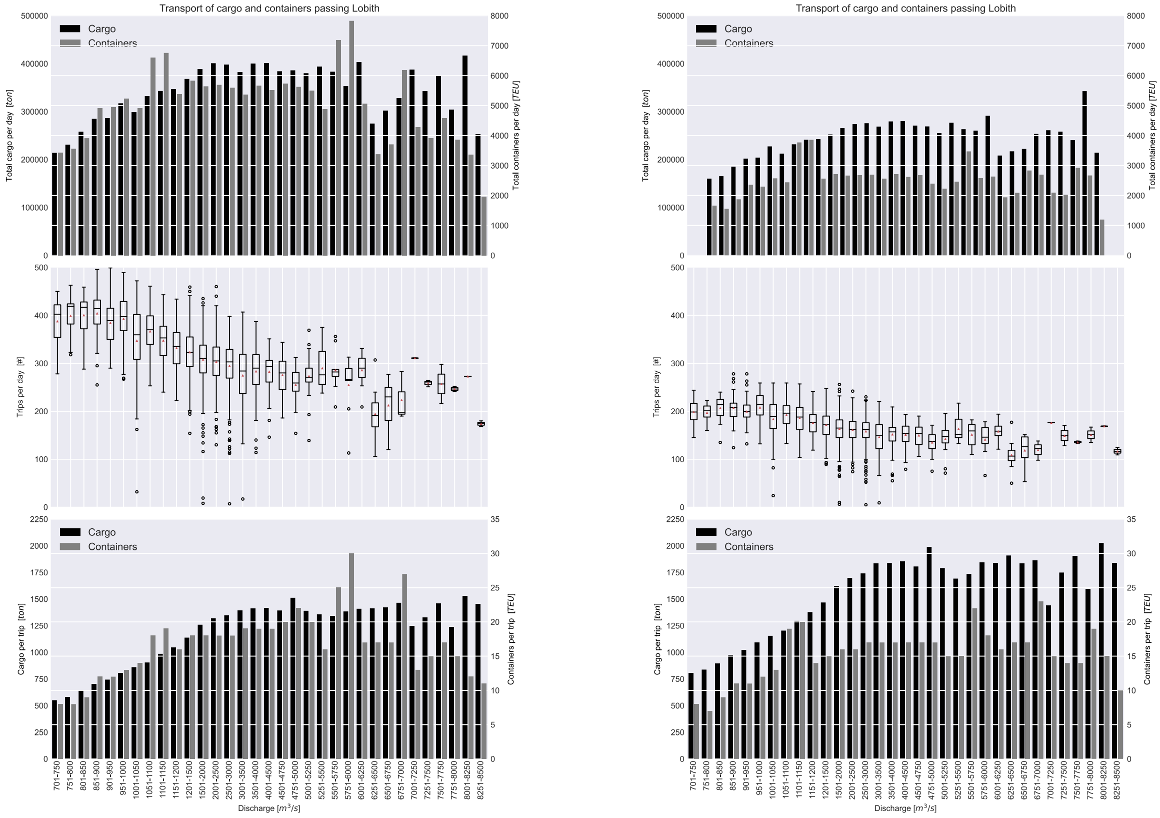
To analyze the vessel deployment for different cargo types the IVS data is filtered on the characteristics of the specific cargo. An overview of the applied filtering is given below:

- Dry bulk: origin = Rotterdam, destinations near Duisburg;
- Liquid bulk: origin = Rotterdam, destinations = Wesseling, Ludwigshafen or Dormagen, vessel type = tankers;
- Containers: origin = Rotterdam, destinations = Duisburg, Emmerich or Mainz, containers = yes.

## 3. Results

This section gives the results of the analyses. We discuss:

1. total fleet performance per discharge bin,
2. vessel class vulnerability for discharge variations,
3. impact of discharge variations on cargo types, and
4. vessel deployment on different supply chains from Rotterdam to Germany.



(a) All passages at Lobith (b) Rotterdam-Germany passing Lobith

**Fig. 4.** Observations, number of trips, volume and TEU per trip for all discharge events in the period 2010–2020.

### 3.1. *Total fleet performance per discharge bin*

This section discusses fleet performance per discharge bin, expressed in number of trips, transported cargo and transported containers in TEU for all vessels passing Lobith (Fig. 4).

Fig. 4a shows the performance of the total fleet passing Lobith in both directions averaged per day or trip per discharge bin with various origins and destinations in Belgium, Netherlands and Germany. The top panel shows that the total transported cargo per day falls for discharge bins below the 1500–2000 m$^3$/s bin. This specific bin range includes the value of 1800 m$^3$/s for which vessels don't experience problems as reported by De Jong (2019), and the value 1960 m$^3$/s for which normative vessels with a draught of four meter (Table 2) can sail fully loaded at the river Waal as indicated by Ligtenberg (2022).

Fig. 4a's mid-panel shows that the number of trips still reduces slightly for discharges above 2000 m$^3$/s, while the lower panel shows that total amount of cargo transported per trip increases, levelling off at 4000 m$^3$/s. This suggests that vessels can still sail a bit more efficiently at higher discharges, compared to the most common conditions observed in the 10-year dataset.

For discharges below the 1500–2000 m$^3$/s discharge bin, Fig. 4a's mid-panel shows an increasing trend in the number of trips, while the bottom-panel shows a decreasing trend in both the transported cargo per trip in tons and the transported containers per trip in TEU. Ultimately this leads to a reduction of approximately 60% in the total transported cargo per trip compared with the most common conditions, which corresponds with reductions reported by Vinke et al. (2022, cf. Fig. 11) about the 2018 drought. For high discharge events no clear pattern is observed in the transported cargo per trip, but a decreasing trend is observed above 5000 m$^3$/s for the transported containers in number of TEU per trip.

Fig. 4b shows similar results but now limited to those ships that sail from Rotterdam to Duisburg. Again the transported cargo per day drops over the discharge bins below the range of 1500–2000 m$^3$/s. From this bin downward, the number of trips shows an increasing trend (mid-panel) and the total transported cargo and containers per trip shows a decreasing trend (bottom-panel). Compared with Fig. 4a the observed reduction in transported cargo per trip is larger: approximately 75% for ships sailing from Rotterdam to Duisburg, compared with 60% for all ships passing Lobith starting in Rotterdam.

From the 1500–2000 m$^3$/s bin upward, the transport efficiency again shows a mild increasing trend, this time up to the 4500 m$^3$/s bin. Above this bin the total transported cargo shows a decreasing trend, while the transported containers remains more or less constant. Beyond the 8000 m$^3$/s a clear drop in transported containers can be observed, however. Based on the values determined by

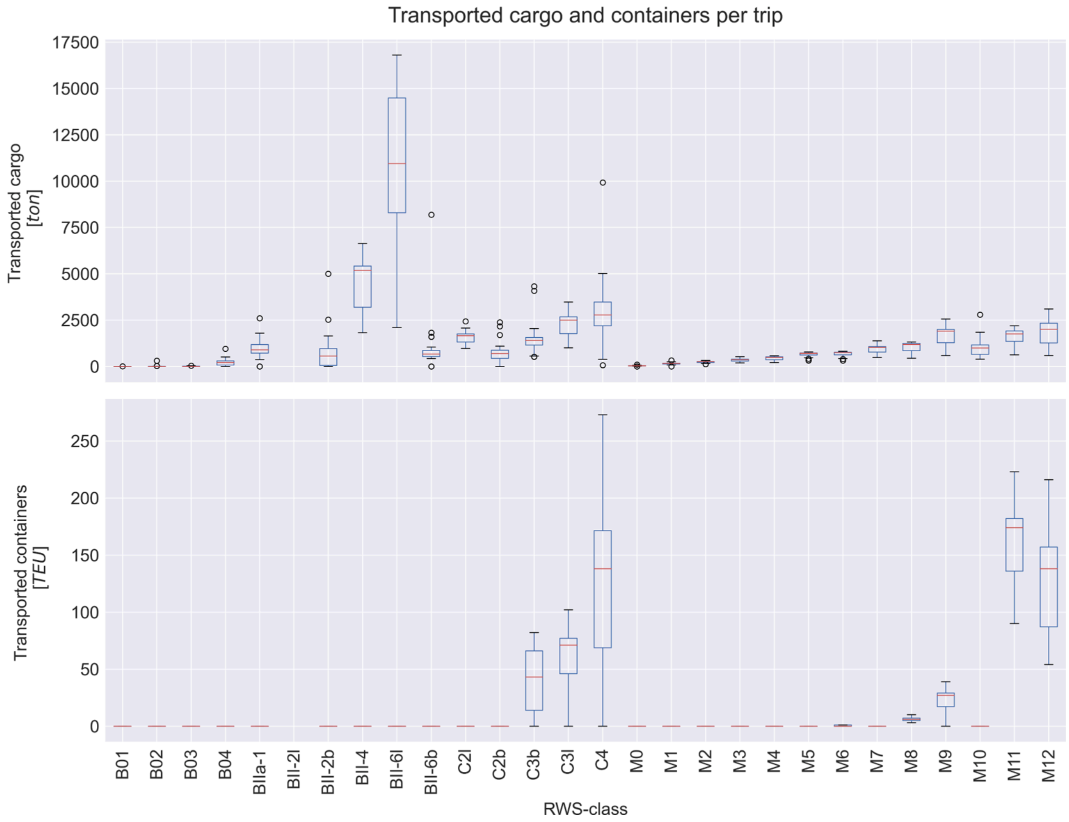


**Fig. 5.** Transported (top) cargo volume per trip and (bottom) containers per trip for each vessel class in the IVS dataset.

Van der Wijk and De Jong (2021) this might be an effect of 4-layer container transport that is affected for discharge events between 5500 m$^3$/s and 11.500 m$^3$/s for standard respectively high-cube containers at the river Waal. Also the regulations in Germany during high discharge events might play a role if water levels exceed the Marke II-level. Above this specific water level inland shipping is suspended.

The difference in number of trips and volume between panels (a) and (b) can be explained by the fact that the Rotterdam - Duisburg corridor is dominated by the four and six barge push-tow units that transport coal and iron in relative large volumes per trip. The results demonstrate that changes in behavior are most noticeable for discharge events below 2000 m$^3$/s and above 5000 m$^3$/s.

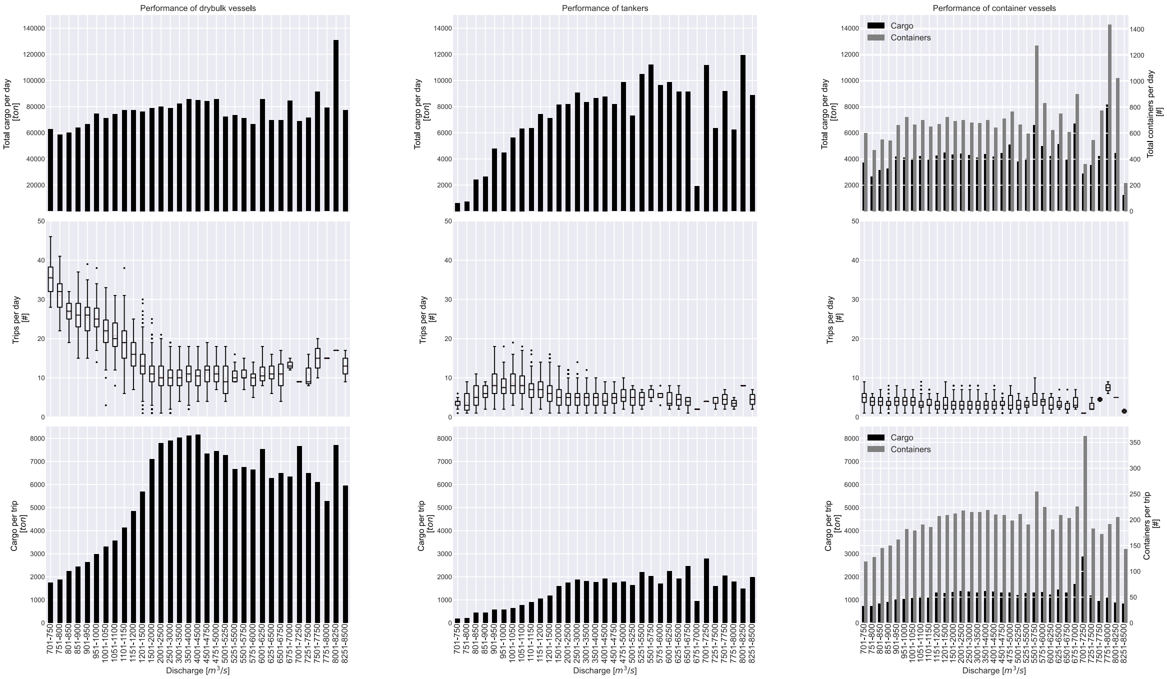
### 3.2. *Vessel class vulnerability for discharge variations*

In the previous section corridor performance, based on average transported cargo volume and number of containers per trip, was described. This does not yet provide insight into the performance of individual vessel types and their potential vulnerability for low or high discharge events.

Fig. 5 gives box-and-whisker plots of (top) the average transported cargo volume (in tons per trip), and (bottom) the average transported containers (in TEU per trip), for each vessel class in the 10-year IVS dataset. The statistics in Fig. 5 are derived from the total fleet passing Lobith.

Fig. 5's top-panel shows box-and-whisker plots of the average transported cargo volumes per trip per vessel class for the entire IVS data set. For the whiskers the default method of 1.5 × IQR is used, meaning that the whiskers extend no further than 1.5 times the Inter Quartile Range (viz. Q3 - Q1) beyond the box edges, that in turn corresponds with the first and third quartiles. Vessel classes where the box and whiskers show a wide variance are most vulnerable to changing discharges. For the average transported cargo (in tons per trip) the most vulnerable vessel classes are BII-4, BII-6 l, C3l, C4 and the motor vessels M9-M12. Based on the vessel characteristics given in Table 2 we can see that these vessel classes have a fully loaded draught of 3.5 or 4.0 m. It is not surprising that these vessels will experience draught restrictions sooner than others vessel classes that sail at a smaller draughts. Fig. 5's top-panel also shows that the transported volume by these vessels under low discharge is still larger than the smaller vessels, e.g. the lowest volume of BII-4 and BII-6 l is almost for all discharge events larger than all the other smaller vessels. This suggests that transport by larger vessels under low discharge events might still be more effective then by smaller vessels, although they are more vulnerable for shallow water conditions.

Fig. 5's bottom-panel shows that container transport between Rotterdam and the German hinterland is mainly executed by the deployment of the large coupled units (C3b, C3l, C4) and larger motor vessels (M9, M11 and M12). All other vessel classes return



(a) Dry bulk (b) Liquid bulk (c) Containers

**Fig. 6.** Number of observations and Performance Indicators: number of trips, transported volume and TEU's per trips per cargo type: (a) dry bulk, (b) liquid bulk, and (c) containers.

values of zero of near zero. The coupled unit C4 show the largest variance. This is probably associated with the fact that this vessel type has a large capacity per layer (Koedijk et al., 2020). Load reductions related to limited head clearance, for example, would result in a load reduction of approximately 160 TEU per layer.

### *3.3. Impact of discharge variations on cargo types*

As shown in the previous section cargo is transported via the Rhine by different types of vessels. Depending on the type of cargo some vessel types are more suitable to deploy than others.

Fig. 6 shows the performance of the (a) dry bulk, (b) liquid bulk, and (c) container transport for all vessels passing Lobith in outbound direction. All the panels show that transport of cargo per day decreases below the 1500–2000 $m^3/s$ discharge bin, similar to the results in Fig. 4. For lower discharges the transported cargo per trip drops, but the shape of the decreasing trend is different per cargo type. Dry bulk and tankers show a convex decline, while container transport displays a more concave decline.

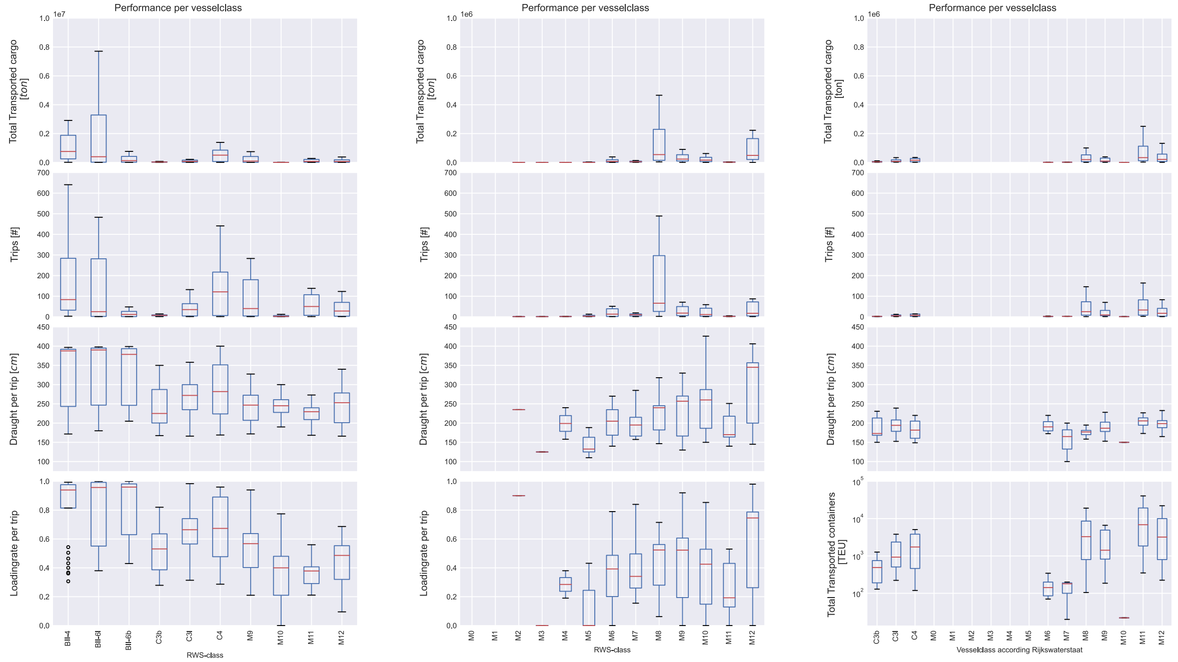
For dry bulk vessels and tankers, the number of trips per day shows an increasing trend for discharges below 2000 $m^3/s$, while such an increase is not observed for the container vessels (possibly due to the fact that container transport often follows fixed sailing schedules). Below 900 $m^3/s$ the number of trips of tankers drops, which is not shown by dry-bulk and container vessels. An explanation might be that the amount of transported cargo per trip decreases significantly because tanker operators are not willing to pay the high operating costs during these low discharge conditions. Compared to the other cargo types it is worth noting that the total number of trips carried out by dry bulk vessels is significantly larger than the other cargo types. This implies that a larger fleet is available for dry bulk transport during dry periods.

For higher discharge events, above 3000 $m^3/s$, a slightly decreasing trend is observed for the transported volume per trip in case of the dry bulk vessels, tankers and container vessels. The container transport per trip (in TEU) shows a similar pattern. The pattern is quite irregular and no distinct behavior can be identified.

### *3.4. Vessel deployment on different supply chains from Rotterdam to Germany*

In the previous section the performance of the total fleet used for different types of cargo was discussed. A further analysis of fleet performance on a more aggregate level is discussed in this section. The results of three main supply chains via the Rhine from Rotterdam to Germany are shown:

1. dry bulk from Rotterdam to the ports near Duisburg;
2. liquid bulk from Rotterdam to the ports Wesseling Hafen, Ludwigshafen or Chempark Dormagen hafen, and



(a) Dry bulk (b) Liquid bulk (c) Containers

**Fig. 7.** Number of observations and Performance Indicators: number of trips, transported volume and TEU's per trips per cargo type: (a) dry bulk, (b) liquid bulk, and (c) containers.

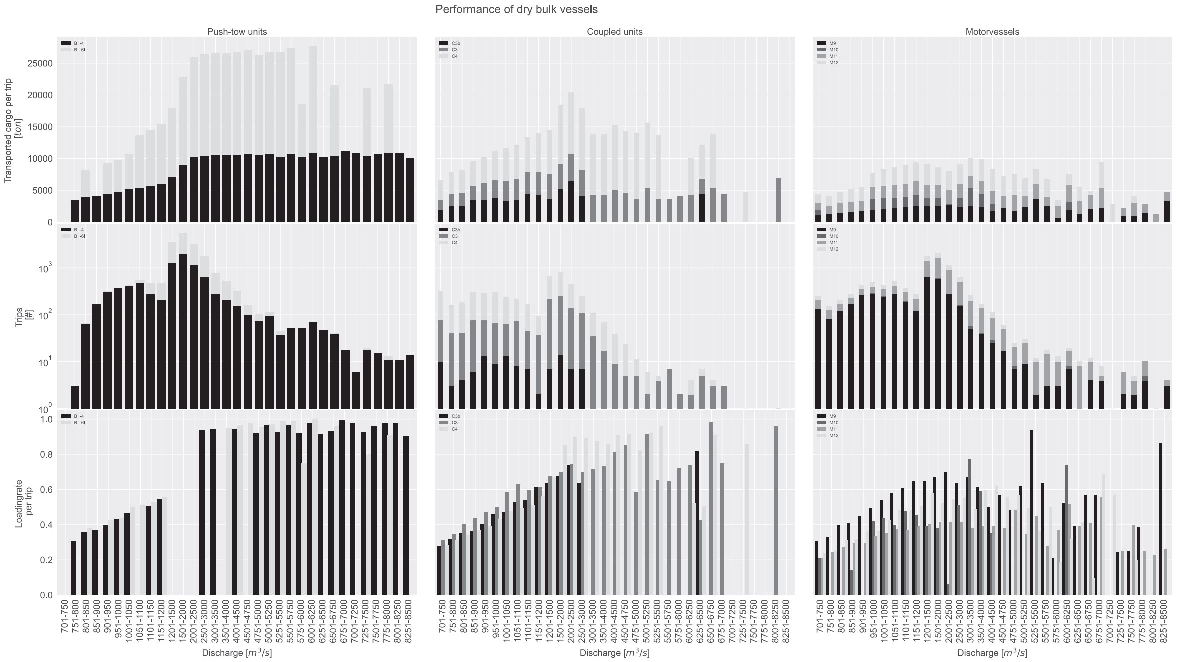


**Fig. 8.** Performance of dry bulk vessels.

3. containers from Rotterdam to the ports Duisburg, Emmerich or Mainz.

Fig. 7 shows the performance of the vessel classes that are deployed to transport dry bulk, liquid bulk or containers. It demonstrates that dry bulk is transported by a mix of push-tow units, coupled units and motorvessels, while liquid bulk is only transported by

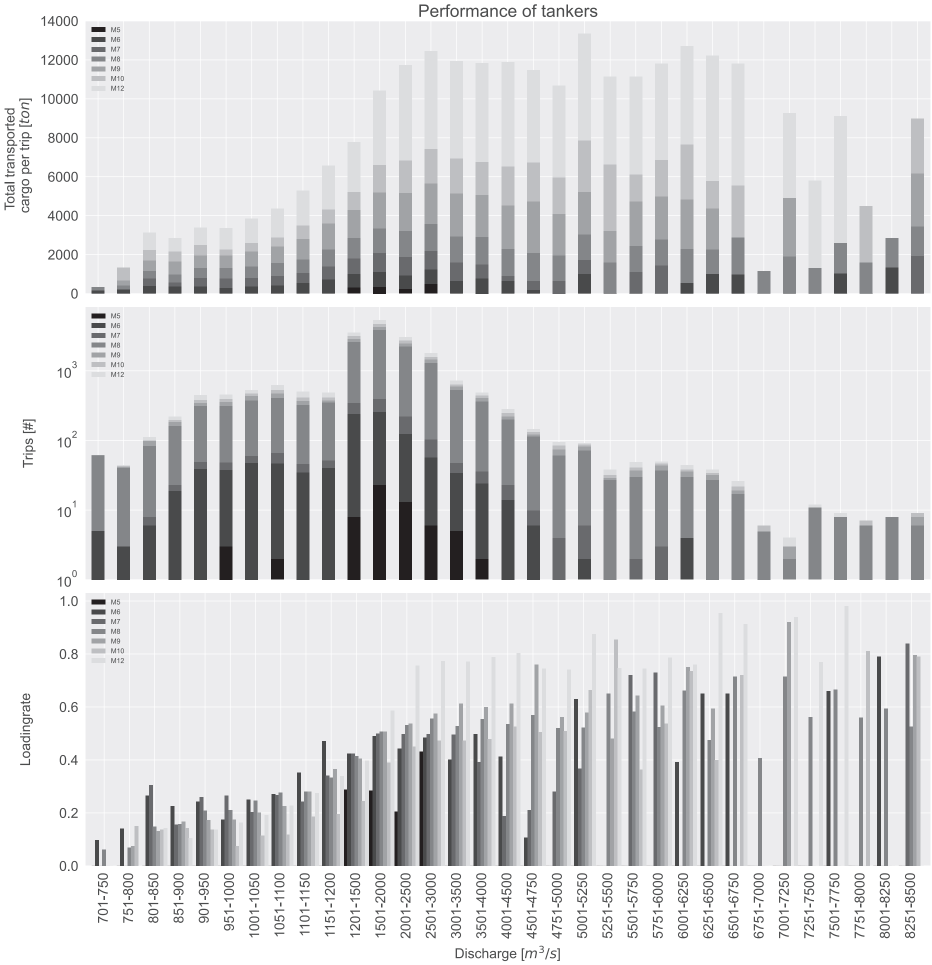


**Fig. 9.** Performance of Tankers.

motorvessels and containers by a mix of coupled units and motorvessels (Table 2).

In Fig. 7a it is observed that large push-tow units, in BII-4, BII-6 l, C3l and C4 formation, are dominant in the transport of dry bulk. Motorvessels of types M9, M11 and M12 are also used for this type of cargo. The spread in the box-and-whisker plots show that these vessel classes are sensitive for changing discharge conditions. A proper deployment of these vessels in climate impact assessments is therefore important in order to get representative results.

Fig. 7b shows that vessel classes M4-M12 are mainly used for transport of liquid bulk. The spread of the box-and-whisker plots show that most of these vessels are vulnerable to changing discharge events. The panel with the number of trips shows that the classes M8 and M12 are most deployed and have a high variance.

Fig. 7c shows containertransport passing Lobith is mainly executed by the coupled units C3b, C3l, C4 and the motorvessels M6, M7, M8, M9, M11 and M12. The motorvessels M8, M9, M11 and M12 display the largest variability under varying discharges. The motorvessels have a potential stacking height of four layers, but the capacity per layer is 52 TEU for the M8 and M9 respectively 102 TEU for M11 and M12. If both vessel types have to reduce the stacking height due to insufficient airdraught the impact is much larger for M11 and M12 motorvessels.

### 3.4.1. Dry bulk

Dry bulk is a large part of the total transport via the river Rhine passing Lobith. From Rotterdam to the inland ports near Duisburg a continuous supply of iron ore and coal is required for the production processes of the industries related to steel and energy production.

Fig. 8 shows the total performance of all vessel types deployed for transport of dry bulk as a function of daily average discharges. The left panel shows that the share of the six-barge push-tow units has a steeper decline for low and high discharges compared to the decrease of the four-barge units. The deployment of the six-barge push-tow units stops below and above the discharge values, following the earlier described regulations regarding push-tow units with six barges. For low discharges a small increase of the number of trips and transported volume is observed for the four-barge push-tow units. This means that the loss of capacity of the six barge formation is substituted by the four barge formation. The same behaviour is observed for high discharge events, which is also related to regulations

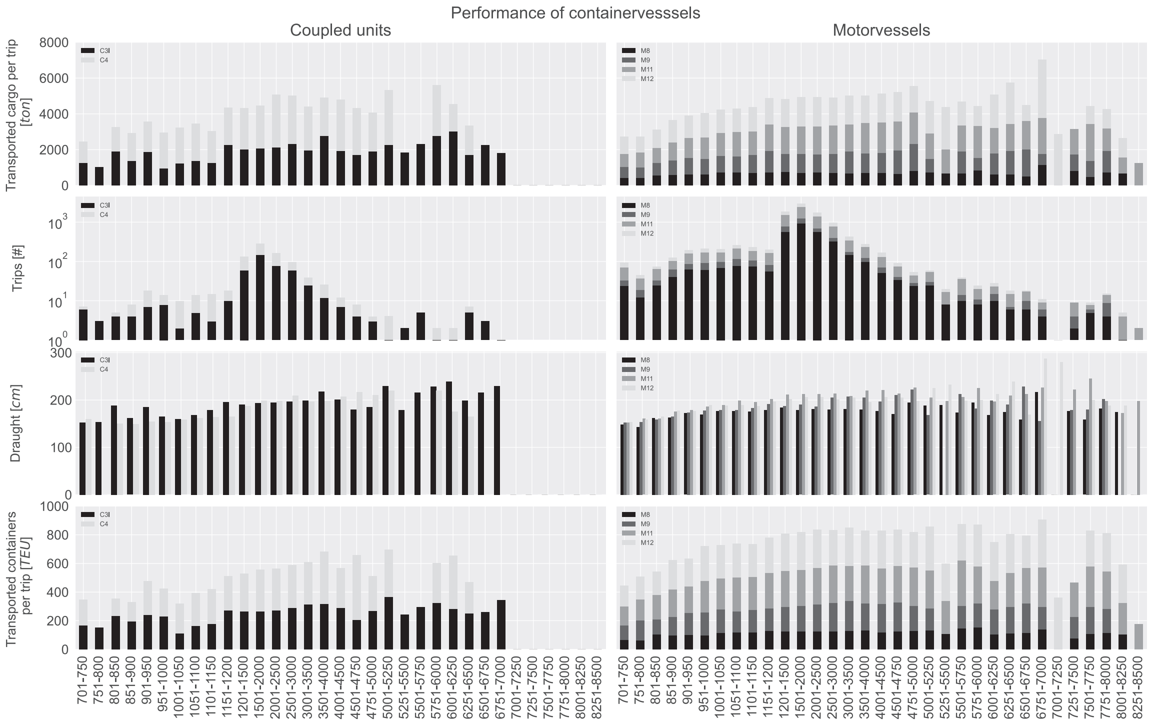


**Fig. 10.** Performance of containervessels.

for the deployment of six barge push-tow units.

For the coupled units (middle panel) and motorvessels (right panel) a substitution by other vessel types is not observed. These vessel types have to adapt to the available navigable draught. Based on the number of passages/trips for high discharge events it seems that the deployment of the C3b- and C4-formation of the coupled units is substituted by the C3l-formation. The width of a C3l-vessel is smaller than the C3b- and C4-formation. Under high discharge events navigation from Rotterdam to Germany experiences higher resistance due to the higher flow velocities, resulting in higher fuel consumption. For low discharge events the motorvessels adapt to the available waterdepth and no clear substitution to other or smaller vessel is observed.

The change in different formation for push-tow units and coupled units is applied to optimize the transport capacity of the fleet. This behaviour should be included in climate impact assessments in order to get representative results.

### 3.4.2. *Tankers*

Fig. 9 shows the performance of tankers. It shows that the vessel classes M5, M6 and M8 have the largest contribution to the total transport of liquid bulk for discharges between 1500 and 3000 $m^3/s$. In the range of 850–4500 $m^3/s$ it is dominated by the M6 and M8 vessels, although the deployment of M5-vessels is observed. Above 4500 $m^3/s$ the deployment of M6 vessels decreases and is taken over by M7 vessels. Remarkable is the observation that the M8 class is present in all the discharge bins and the share of the larger vessels M10 and M12 is relative small. This implies that the M8 vessel is the most suitable vessel for liquid bulk transport.

In comparison to dry bulk, Fig. 8, no substitution by an other vessel class is observed. Tankers are dedicated vessels for transport of liquid bulk. Pushtow units or coupled units are not available or only in relative small numbers. Therefore tankers have to adapt under low discharges and no other suitable vessels are available to compensate the loss of capacity. The relative large difference in loading rate between low and high discharges will have a strong effect on the deployment of tankers at the Rhine for future droughts or high discharge events, but also on the availability of tankers in supply chains on other corridors.

### 3.4.3. *Container transport*

The performance of the coupled units and the motorvessels is shown in Fig. 10. Above 7000 $m^3/s$ the coupled units C3l and C4 vessels are no longer deployed, while the motorvessels are still sailing under these conditions. Although it should be mentioned that the motorvessels show a irregular pattern. The loss of capacity of the coupled units, does not seem to be compensated by increased deployment of motorvessels. Van der Wijk and De Jong (2021) derived that specific values at the Waal are 5.580 and 11.454 $m^3/s$ for four-layer transport High-Cube respectively standard containers. In practice a mix of High-Cube and standard containers is used, so between these values barge operators have to decrease the stacking height due the available headclearance. The observed behavior suggests that motorvessels are not capable to subsitute the lost capacity of the coupled units.

Container transport on this corridor depends on the navigable conditions and the regulations in the Netherlands and Germany. German regulations are related to MarkeII-levels which cause differences in the available headclearance for high discharges (De Jong and Van der Wijk, 2020). This affects the capacity of vessels that sail along the whole corridor up to Mainz.

For very low discharges below 900 $m^3/s$ it is observed that the share of the coupled unit C3l becomes larger compared to the C4 units. For these discharge events the width of the fairway on the Rhine varies a lot and a potential minimum width of approximately 89 m (Verschuren, 2020) which is significantly less than the required width of 150 m (Central Commision for the navigation of the Rhine, 2020). For these discharges safety becomes an issue comparable to the push-tow units for dry bulk transport. All the motorvessels show the same behavior and an increase of the deployment of a specific vessel class is not observed.

The above-described phenomena have not been included in current impact studies. They should be included in climate impact assessments in order to get representative results. The observed inland shipping behavior can be implemented in logistic simulation packages that are capable to assign specific tasks to individual agents (Kievits, 2019; Wienk, 2021; Vinke et al., 2022).

## 4. Discussion

The combined analysis of IVS and discharge data revealed a number of important aspects in the behaviour of IWT vessels that should be included in climate assessments to achieve representative results. To properly interpret the findings it is important to address some issues related to the data and methods used. IVS-data rely to some extent on manual inputs by the vessel captains, e.g. the draught and height of the vessels. This is known to lead to data inaccuracies. Also differences in the number of trips might be present which is discussed by Verschuren (2020). Where possible cross checks with other data sources, like AIS-data, have been made to double check the accuracy of indicators like the number of trips. Since 2019 Rijkswaterstaat has merged IVS and AIS into IVSNext partly to address this issue. While it is known that the IVS data may not be 100% accurate, we are still confident that the *trends* reported in this paper are representative.

The selection of the discharge bins is based on a statistical analysis and values used by IWT in practice or described in regulations. It seems that significant changes occur within the 1500–2000 $m^3/s$ bin. Another option is to define a relation based on a regression method for a range of discharge bins that has been used by Verschuren (2020). Her detailed research show similar results compared to our outcomes but she focused more on a specific range of low discharges and four time periods in 2018. For future analyses it may be needed to increase the bin resolution around this point to gain more detailed insight into the prevailing behavior.

As shown in Fig. 4 the outcome of the analysis depends on the selected corridor. As a consequence it is good to realise that the results presented in this paper are connected to a specific corridor. The method itself can obviously be applied for other corridors in Europe (Schweighofer, 2014) and worldwide or other counting locations as well. The analysis may give different results, depending on cargo and vessel types on the corridor (De Jong, 2020a). This corridor sensitivity only underlines the importance to analyse fleet behaviour under varying discharges for accurate climate impact assessments.

The analysis has been executed for the time period 2010–2020. It should be mentioned that the observations for low water events are mainly of the year 2018 and within the selected time period there was only one extreme low water event. Additional datasets of past extremes could result in more observations for low and high discharges. Ligtenberg, 2022 used a dataset for the period 2004–2020 but he examines the share of each vessel class on a yearly basis for the same counting location. It should also be noted that the fleet from much earlier periods may no longer be representative for the system's current state (Quist et al., 2011), so older datasets might not provide better insights in the response of inland shipping.

In this research we assume that the discharge level is the main driver that influences the performance of IWT during extreme discharge events. In practice other drivers, e.g. oil prices and industrial production, may also impact IWT performance. Such drivers were not included in this study.

## 5. Conclusions

This paper notes that existing literature typically takes (a small number of) representative vessels and estimates corridor scale climate risks through extrapolation. Newspaper articles and reports from the sector around recent extreme discharge events suggest that more complex vessel behaviour could be at play. In response this paper analyses 10 years of IVS and discharge data to reveal how fleet composition and vessel deployment on the river Rhine respond to varying discharge conditions. From the analysis we draw the following conclusions:

### 5.1. Dry bulk

- Dry bulk on the river Rhine is pre-dominantly transported by large push-tow units in BII-4, BII-6 l and the coupled units in C3l and C4 formation. Motorvessels of types M9, M11 and M12 are also used for dry bulk transport.
- Deployment of the very large BII-6L convoys is restricted by waterway regulations (sailing prohibited below 1086 $m^3/s$ and above 6098 $m^3/s$). When BII-6L convoys are no longer allowed to sail, part of their load is handled by the smaller BII-4 convoys (substitution).
- While progressing towards the low discharge extreme the contribution of BII-4 type convoys reduces. This loss in transport capacity is partly covered by coupled units and motorvessels that progressively need to reduce their loading rate as water levels drop (adaptation). The phenomena were already observed by Vinke et al. (2022).
- A mix of vessel classes is used to transport dry bulk, so there is a relatively high redundancy in the dry bulk fleet on the river Rhine. As a consequence this cargo type is less vulnerable to low discharge extremes (provided this redundancy remains).

- For high discharge similar behavior is observed for the push-tow units BII-6 l and BII-4, while a strong reduction of the deployment of the coupled units and motorvessels is observed. In this situation the redundancy is much lower.

### 5.2. Liquid bulk

- Liquid bulk on the river Rhine is pre-dominantly transported by motorvessels of types M4-M12. Of these the M8, M9, M10 and M12 types handle the most trips with the largest average volume per trip and are deployed over a wide range of discharge bins. This implies that although large vessels are more vulnerable to especially low water dephts, these vessels are economic efficient over a wider discharge range compared to smaller tankers.
- As discharges reduce from 3000 $m^3/s$ downward loading rates are gradually reduced to adapt to reduced available water depths. The larger number of trips cannot compensate for the lower loading rates however, causing the total transported volume to decrease towards the lower discharge extreme.
- Since liquid bulk on the Rhine corridor is transported exclusively with motorvessels there is hardly any redundancy in the fleet to compensate in case of reduced transport capacity. As a consequence liquid bulk transport on the river Rhine is relatively vulnerable to low discharge extremes.

### 5.3. Containers

- Containers on the Rhine corridor are predominantly transported by a fleet mix that consists of coupled units C3b, C3l and C4 and motorvessels M6, M7, M8, M9, M11 and M12. In general all vessel classes are deployed over the whole range of discharge bins, so no redundancy is present.
- Compared to dry and liquid bulk, container transport does not show an increase in the number of trips as discharge levels reduce. This is possibly due to the fact that container transport often follows fixed sailing schedules on this corridor.
- Compared to dry and liquid bulk, container transport is vulnerable to high discharge events in the case of limited air draught along a route. In such cases vessels may have to reduce their stacking height. Larger vessels are affected more by this phenomenon due to the larger capacity per layer.

### 5.4. Conclusions

- Fleet composition and vessel deployment have a significant impact on how the transport of different cargo types varies with varying discharges. Vessel behaviour will be corridor specific and a detailed and situation specific study should be included in any climate impact assessment.
- Fleet behaviour under low or high water events depends on the types of vessel (push-tow units, coupled barges or motorvessels). Most vulnerable are, obviously, those vessel types that have the largest loaded draughts or highest head clearance. But it is good to be aware of the fact that waterway regulations may apply that restrict vessel deployment, or place restrictions on use of the waterway that affect capacity (i.e. maximum speeds, no overtaking, water preserving lock regimes, etc).
- Fleet redundancy can be an effective mitigation measure protecting against the effects of climate change. Depending on the number of available vessel types or classes each type of cargo has a high or low level of redundancy.
- Low discharge extremes typically have a much larger impact on IWT performance than high discharge extremes. This is mainly due to the fact that low discharge extremes typically persist much longer (weeks-months) than high discharge extremes (hours-days). Therefore modelling vessel deployment and fleet composition differently under low and high discharge events for individual cargo types is important to simulate in future climate impact assessments or evaluation of measures.

Our research demonstrated for the first time how inland shipping behavior correlates with a wide variety of discharge values over a longer time period. We presented that behavior of dry bulk, liquid bulk and container transport differ as a result of the different types of vessels that are deployed. Regulations that are applicable during low and high discharges to specific vessel classes play an important role in the observed behavior. The identified behavior of the individual vessel types and classes in this research should be implemented in logistic simulation tools to improve climate risk assessments.

**Acronyms**

| | |
|---|---|
| **AIS** | Automatic Identification System |
| **ALR** | Agreed Low River discharge |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IVS** | Informatie- en VolgSysteem voor de Scheepvaart |
| **IWT** | Inland Water Transport |
| **VTS** | Vessel Traffic Service |

**Table 2**
Vessel CEMT-class descriptions and draught data combined with the vessels RWS-class for ships navigating the river Waal (Koedijk et al., 2020; ten Hove et al., 2017 and Roelse et al., 2002).

| | **CEMT class** | **RWS class** | **Description** | **Beam** [m] | **Length** [m] | **Draught [m]** loaded | empty |
|---|---|---|---|---|---|---|---|
| **Coupled units** | I | C1b | 2 Péniches wide | 10.1 | 38.5 | 2.5 | 1.2 |
| | I | C1l | 2 Péniches long | 5.05 | 80 | 2.5 | 1.2 |
| | IVb | C2l | IV + Europe I long | 9.5 | 180 | 3.0 | 1.0 |
| | Vb | C3l | Va + Europe II long | 11.4 | 180 | 3.5 | 1.8 |
| | VIa | C2b | IV + Europe I wide | 18.5 | 103 | 3.0 | 1.0 |
| | VIa | C3b | Va + Europe II wide | 22.8 | 105 | 3.5 | 1.8 |
| | VIb | C4 | Va + 3 Europe II | 22.8 | 185 | 3.5 | 1.8 |
| **Push-tow units** | I | B01 | barge pushed convoy | 5.2 | 55 | 1.9 | 1.7 |
| | II | B02 | barge pushed convoy | 6.7 | 61 | 2.6 | 1.8 |
| | - | B03 | barge pushed convoy | 7.5 | 78 | 2.6 | 1.8 |
| | III | B04 | barge pushed convoy | 8.2 | 85 | 2.7 | 1.8 |
| | IV | BI | Europe I convoy | 9.5 | 94 | 3.0 | 1.8 |
| | Va | BII | Europe II convoy | 11.4 | 92 | 3.5 | 1.8 |
| | Va | BIIa-1 | Europe IIa convoy | 11.4 | 110 | 3.5 | 1.8 |
| | Va | BIIl-1 | Europe IIa convoy long | 11.4 | 136 | 3.5 | 1.8 |
| | VIa | BII-2b | 2 barge pushed convoy wide | 22.8 | 105 | 4.0 | 2.0 |
| | VIb | BII-4 | 4 barge pushed convoy | 22.8 | 193 | 4.0 | 2.0 |
| | Vb | BII-2 l | 2 barge pushed convoy long | 11.4 | 185 | 4.0 | 2.0 |
| | VIIa | BII-6b | 6 barge pushed convoy wide | 34.2 | 195 | 4.0 | 2.0 |
| | VIc | BII-6 l | 6 barge pushed convoy long | 22.8 | 270 | 4.0 | 2.0 |
| **Motorized vessels** | 0 | M0 | Remaining | 5.0 | 28 | - | - |
| | I | M1 | Péniche (Spits) | 5.1 | 39 | 2.5 | 1.2 |
| | II | M2 | Kempenaar | 6.6 | 55 | 2.6 | 1.4 |
| | III | M3 | Hagenaar | 7.2 | 70 | 2.6 | 1.5 |
| | III | M4 | Dortmund Eems | 8.2 | 73 | 2.7 | 1.5 |
| | III | M5 | Ext. Dortmund (Verlengde Dortmunder) | 8.2 | 85 | 2.7 | 1.5 |
| | IVa | M6 | Rhine Herne vessel (Rijn Herne Schip) | 9.5 | 85 | 2.9 | 1.0 |
| | IVa | M7 | Ext. Rhine Herne (Verlengde Rijn Herne) | 9.5 | 105 | 3.0 | 1.0 |
| | Va | M8 | Large Rhine vessel (Groot Rijnschip) | 11.4 | 110 | 3.5 | 1.8 |
| | Va | M9 | Ext. Large Rhine vessel (Verl. Groot Rijnschip) | 11.4 | 135 | 3.5 | 1.8 |
| | VIa | M10 | Rhinemax vessel | 13.6 | 110 | 4.0 | 2.0 |
| | VIa | M11 | Rhinemax vessel | 14.2 | 185 | 4.0 | 2.0 |
| | VIa | M12 | Rhinemax vessel | 17.0 | 135 | 4.0 | 2.0 |

## 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.

## Data availability

The data can be requested via or found at the links provided in the sections of materials and methods.

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## Appendix A

See Table 2.

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