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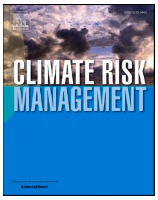

Cascading effects of sustained low water on inland shipping

Frederik Vinke [a,b,*], Mark van Koningsveld [a,c], Cornelis van Dorsser [a,d], Fedor Baart [a,e], Pieter van Gelder [f], Tiedo Vellinga [a]

[a] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Ports and Waterways section, P.O. Box 5048, 2600 GA Delft, The Netherlands*
[b] *Rijkswaterstaat, P.O. Box 2232, 3500 GE Utrecht, The Netherlands*
[c] *Van Oord Dredging and Marine Contractors B.V., P.O. Box 8574, 3009 AN Rotterdam, The Netherlands*
[d] *Trends and Transport B.V., Langesteijn 102, 3342 LG Hendrik Ido Ambacht, The Netherlands*
[e] *Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands*
[f] *Delft University of Technology, Faculty of Technolgoy, Policy and Management, Safety and Security Science section, Delft, P.O. Box 5015, 2600 GA Delft, The Netherlands*

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ABSTRACT

The river Rhine is one of Europe's busiest waterways and is part of the Rhine-Alpine corridor. In 2018 the river experienced a severe low discharge extreme. This impacted the river's transport capacity for a period of several months, causing shortages of source materials and fuels in regions far in-land. Historically, prolonged droughts of this magnitude are not uncommon. Concerns have been raised, however, that climate change may further increase their frequency and severity. Additionally the increased proportion of larger vessels in the overall fleet composition has made the supply of cargo via the river Rhine more vulnerable to reduced water depths. A better understanding of the risks and effects of sustained low water levels for Inland Waterway Transport network performance is therefore essential to enable sensible mitigation. An integral model that explicitly links the state of the river to supply chain performance at the scale of corridors, however, appears to be not yet available. This paper suggests a novel method to explicitly include the cascading effects of low discharge events (and mitigating measures) in climate risk assessments of waterborne supply chain performance, at system level. It is shown that its implementation can describe cascading effects and climate risks for fleet management and terminal operation.

1. Introduction

Inland Water Transport (IWT) is an important way of transport that is generally considered environmentally friendly and safe and as such provides a competitive alternative to road and rail transport (Wiegmans and Konings, 2017). It contributes to decongesting road networks, and has significant capacity for increased exploitation. The river Rhine is the main waterway for the IWT modality and

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Abbreviations: ABS, Agent Based Simulation; AIS, Automatic Identification System; ALR, Agreed Low River discharge; BIVAS, Binnenvaart Analyse systeem; DES, Discrete Event Simulation; IVS, Informatie- en VolgSysteem voor de scheepvaart; IWT, Inland Water Transport; O-D, Origin Destination; SIVAK, Simulatiepakket voor de VerkeersAfwikkeling bij Kunstwerken; UKC, Under Keel Clearance.

* Corresponding author at: Delft University of Technology, Faculty of Civil Engineering and Geosciences, Ports and Waterways section, P.O. Box 5048, 2600 GA Delft, The Netherlands.
E-mail address: F.R.S.Vinke@tudelft.nl (F. Vinke).

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one of the busiest freight routes in Europe. About 70 per cent of all inland waterway transport in the former EU-15 member states is transported on the Rhine (Jonkeren et al., 2007). Van Dorsser (2015) states that 50% of the cargo transported from Rotterdam to the hinterland is transported to the area of Duisburg and 25% is transported further to Basel, passing Duisburg. The gradual increase in the proportion of larger and deeper drafted vessels (Groen and Van Meijeren, 2010; Quist et al., 2011) in the overall fleet composition over the past decades made waterborne transport highly economic efficient. The transport of dry bulk (e.g. iron and coals) on the Rhine between the seaport of Rotterdam and the inland port of Duisburg (see Fig. 1) is particularly efficient due to the push tow units in different configurations, up to six barges. While the performance of the waterborne transport on the Rhine compared to other modes of transport is good, in terms of costs and tonnage, it is also vulnerable to the river's hydrodynamics. The IWT system becomes less reliable and the risk of disruptions in the supply chain increases, which is not a favourable condition for the sector and has a negative effect on overall transport cost and carbon emissions from transport. This became particularly evident during the 2018 drought, which lasted over four months. The reduced discharge led to a reduced navigable depth, resulting in a drop in IWT-performance and significant economic loss (Kriedel et al., 2019). Observable effects on IWT, among others, were an increase in traffic intensity, an increase of arrivals at terminals and queue formation, a higher filling degree of the stocks in sea ports, and delays in the supply of goods to the hinterland. All this caused disruptions in the industrial production (Reguly, 2020) or depletion of national strategic reserves: e.g. fuel supply to Germany and Switzerland (Kirschbaum, 2018). For Germany this disruption was associated with a decrease of industrial production by 5 billion Euros (Ademmer et al., 2019; CCNR, 2019). The loss of transport capacity and performance of IWT could not be compensated by the other transport modes e.g. road and rail. The transported volume of dry bulk by these push tow units is very large compared to the available capacity of trucks and trains. The required number of trucks would potentially cause a lot of traffic congestion at the roads. Although containers can be shipped by an other mode of transport, the capacity of those modes is not sufficient. This demonstrates that low water periods affect the total freight transport corridor between Rotterdam and the hinterland in Germany. Society in Western-Europe relies on cargo transport via the Rhine.

To meet future challenges and secure reliable transport via the river Rhine in the future, adequate and cost effective measures are required (Zheng and Kim, 2017). The evaluation of such measures requires adequate models for estimating the effects of low water on the IWT system and the risks for exposed objects or processes, e.g. vessels or terminal operations. Previous studies on the effect of low water on IWT, focussing on the Rhine area, have typically been based on a coupling of observations and models to study a selection of known bottlenecks (Jonkeren et al., 2007; Van Meijeren et al., 2011; Turpijn and Weekhout, 2011; Van Dorsser, 2015). Based on a relative small number of main bottlenecks and representative vessel-types, impacts for the whole IWT-sector are derived. These

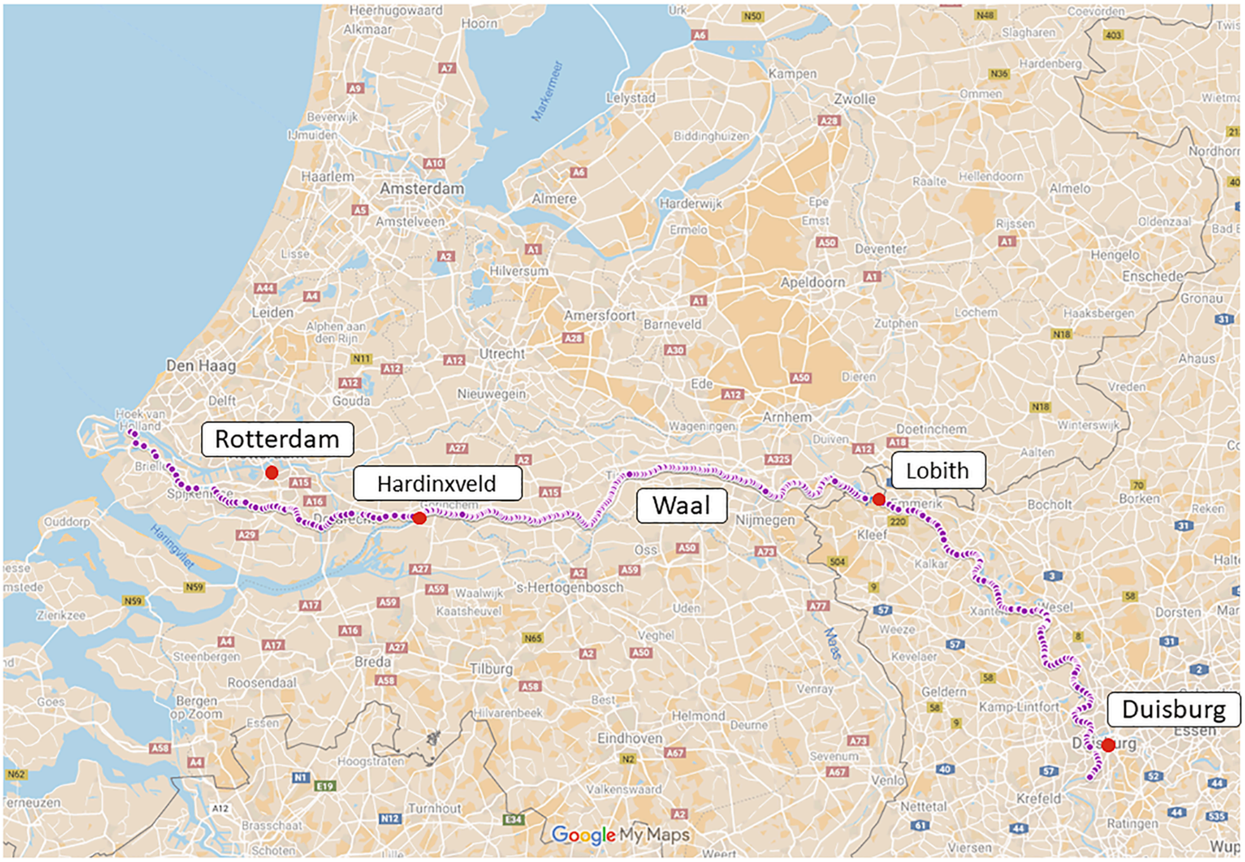


Fig. 1. Corridor between Rotterdam (NL) and Duisburg (GE) via the river Rhine, including the Dutch branch Waal.

principles neglected phenomena as changes in the deployment of vessels, potential issues at the terminals at origin and destination locations, et cetera. Cascading effects on the supply chain from terminal to terminal have not been investigated yet, while an integral model that establishes an explicit and dynamic link between the state of the river and supply chain performance at the scale of corridors does not yet appear to be available. This hampers the design and comparison of sensible mitigation measures. Lawrence et al. (2020) conclude that consideration of cascading impacts in climate risk assessments can minimize the maladaptive responses of decisions for mitigation. Evaluation of potential mitigation measures has primarily been included through expert judgements or in discussion (Van Dorsser, 2015), while simulations have only been done in larger projects (Van Meijeren and Groen, 2010; Van Meijeren et al., 2011). Design and evaluation of mitigation measures requires more detailed insight into system level effects compared to the methods currently published in literature. A more detailed analysis of trade-offs between alternative packages of mitigation measures is increasingly important for decision and policy makers now that the consequences of climate change are experienced more prominently, e.g. in the form of extended dry periods in the Rhine catchment area.

This paper argues the importance of accounting for cascading effects in the waterborne supply chain at the Rhine between Rotterdam and Duisburg during prolonged low river discharges that seems to be a knowledge gap in the current literature. A novel method is proposed to explicitly resolve the effects of low and high discharge events (and mitigating measures) on IWT network performance and risks, using a supply chain approach. To demonstrate the benefits of the novel method, compared with those presented in literature so far, several systemic effects are discussed that have been observed in practice for the transport of iron and coals between Rotterdam and Duisburg, but that previous methods did not resolve explicitly:

1. Changes in number of trips, transported volume and costs;
2. Changes in fleet composition and fleet occupancy;
3. Increased congestion in sea ports by reduced loading rates and increased trip numbers;
4. The dynamic response of transport performance when water levels are changing; and
5. The storage capacity at the destination.

Following the introduction in Section 1, an overview of state of the art methods is given in Section 2. The method for the assessment of the cascadings effects is described in Section 3 and in Section 4 the results of the novel method are shown compared to observed phenomena according IVS-data. A discussion about the strong and weak points of the method is presented in Section 5, before the conclusions and recommendations in Section 6.

2. Literature review – State of the art methods

A comparison is made between several research programs and studies that investigated climate change and its related water level effects on IWT for the river Rhine. The focus of this comparison is on the potential bottlenecks at the Dutch branch the Waal. The goals of the review are: 1) to summarize the approaches and applied models in the current literature and 2) to derive a common approach that is applied (at least in part) in each study. This common approach is reviewed to conclude to what extent the presumed knowledge gap exists.

Within the Climate for Spatial Planning program (2004–2011) Jonkeren et al. (2007) derive annual welfare effects of low water levels on the river Rhine by performing a multiple regression approach on detailed reported trip data, including dry periods. The welfare effects were determined for two bottlenecks by applying a Q-h-relation to determine navigability and the model NODUS to simulate freight flows. They found a considerable effect of water levels on freight price per ton and on the load factor, but observed that effect on the price per trip was close to zero.

The effects of climate change and potential solutions for water transport on the Rhine River between the port of Rotterdam and the German hinterland as far as Koblenz were investigated in the Knowledge for Climate program (2007–2014) (Van Meijeren and Groen, 2010; Krekt et al., 2011; Van Meijeren et al., 2011; Turpijn and Weekhout, 2011). To examine the impact of reduced water levels on inland navigation and traffic intensity, simulations were performed with Binnenvaart Analyse Systeem (BIVAS) (Rijkswaterstaat, 2019b). Based on an origin/destination travel matrix, BIVAS derives the route with the lowest travel cost for each trip, given water depth and vessel draught. Simulations with TRANSTOOLS (EU, 2013) were executed to examine the potential modal split.

The European 7th Framework project ECCONET (Hendrickx and Breemersch, 2012) simulates freight flows under the climate scenarios derived with models used by Szépszó et al. (2014), while the Origin Destination (O-D) matrix was taken from the TRANSTOOLS model. This was then fed into the multi modal transport model NODUS (Beuthe et al., 2012). The cost function for the IWT modality was mainly influenced by the vessel loading rate, and followed the method described by (Jonkeren and Rietveld, 2009). The simulations were executed for known bottlenecks Kaub and Ruhrort on the Rhine River, based on the assumption that the loading rate was the governing parameter of the cost function. The NODUS model ran on 6 to 8 water levels (ranging from unrestricted to severely restricted traffic), with the results of each level reweighted according to the number of days that water level occurred. The results were compared with reference transport scenarios to derive the marginal effects of climate change. Intervention measures were evaluated through implementation in NODUS.

The Second Delta Program focuses on securing the long term flood resilience of the Netherlands (Ecorys, 2011; Ecorys, 2012). Trade and traffic predictions were derived using a combination of freight prediction models from Port of Rotterdam NV and Rijkswaterstaat's traffic prediction model BIVAS. The locking model Simulatiepakket voor de VerkeersAfwikkeling bij Kunstwerken (SIVAK) (Rijkswaterstaat, 2000) was used to assess the additional waiting times associated with placement of locks. These additional waiting times were used as input in a Container Port Competition Model to estimate modal shifts and possible shifts of cargo to competing ports. The model TRANSTOOLS was used, in combination with expert judgements, to further substantiate the selection of the assumptions.

Van Dorsser (2015) identified climate change as one of the external drivers that would have adverse long term effects on the performance of the IWT-system, and the investigations were aimed at examining the potential impact. The study's scope focussed on transport that passes the locations Lobith and Kaub; related to the Ruhr and Kaub market regions and transport capacity for these markets is restricted by the water levels at the selected locations. Van Dorsser (2015) defined a representative vessel for each market. Given the weight-draught relation of the representative vessels and the Q-h relations he derived the maximum loading capacity, barge utilisation and transport costs for both markets.

Christodoulou et al. (2020) analyses the impacts of droughts, on four specific locations of the Rhine and the Danube. Runoff discharge predictions from LISFLOOD are translated to water levels using Q-h relations for four locations. The model TRANSTOOLS is used to translate these demand scenarios to transport activity. The cost or benefits for future scenarios are quantified comparing with the historical frequencies of such events, but the potential impact of water levels on cost is not modelled explicitly.

The project Climate Resilient Networks: Inland Waterways (start 2019), commissioned by Rijkswaterstaat, assesses the impacts of climate change on the IWT network that is maintained by Rijkswaterstaat. For different static discharges at Lobith the navigable conditions at the Rhinebranches and the Meuse are derived. BIVAS-simulations show the future changes in transport cost, transported volume, number of trips and routing in the IWT-network in the Netherlands (De Jong, 2020b).

The project KLIWAS (BMVI, 2015) analyzed the future discharges at the Rhine and the impact on IWT in Germany. Within KLIWAS the package SOBEK (Deltares, 2019) is used to derive water levels and velocities, while a cost structure model is applied to examine how navigation conditions affect ship operation and how the available transport capacity changes.

As seen in Table 1 the most common package to simulate the hydrodynamic river conditions is SOBEK besides the application of a Q-h-relation, while BIVAS, NODUS and TRANSTOOLS are used to simulate transport of waterborne supply chains.

BIVAS includes the navigable conditions derived from water depths simulated with SOBEK for a given discharge or discharge scenario simulated. The transport demand is based on a list of origins and destinations derived from IVS-data. It does not actually resolve the movement of individual vessels nor does it track the actual transport of cargo. The model counts the number of trips that can be made of the predefined list and whether this is done by a load reduction or another route. NODUS (Beuthe et al., 2012) does simulate the operational activities at platforms and terminals (loading, unloading, moving, waiting and/or transit, transhipping). Compared with BIVAS the inclusion of other modalities adds to the understanding of system effects. A drawback of the model is that it does not directly take into account the effect of different water levels on the capacity and costs of inland ships. While BIVAS takes water levels into account, it doesn't actually resolve the transport (only trips and traffic intensity). In contrast NODUS and TRANSTOOLS do resolve cargo flows, but don't integrate the effect of different water levels on the capacity and costs of inland ships. None of these models resolve cascading effects of water levels through multiple interconnected supply chains. The pros and cons of the different models and applications are summarized in Table 2.

In the current literature it is found that IWT related climate impact assessments, so far, have mainly focused on the anticipated transport cost increase for a range of scenario's. In most of the studies the loading rates are derived based on Q-h-relations for monthly discharge scenarios or simulated for a number of stationary discharges, but daily discharge data/projections are not used to determine daily varying loading rates (Jonkeren et al., 2007; Jonkeren, 2009; Hendrickx and Breemersch, 2012; Van Dorsser, 2015; Christodoulou et al., 2020). In comparison to these projects, in the KLIWAS-project daily varying discharges were used, but vessel deployment or predescribed activities for individual vessels was/were not included. A method that includes daily varying navigable depths and applies these to vessel deployment is not described in the current literature. The studies reviewed above often focus on a number of known bottlenecks Ruhrort and Kaub (Rhine) (Jonkeren et al., 2007; Jonkeren et al., 2011; Hendrickx and Breemersch, 2012; Beuthe et al., 2012; Beuthe et al., 2013; Jonkeren et al., 2014; Van Dorsser, 2015; Christodoulou et al., 2020). Focussing on bottlenecks is often justified by the fact that the impact on IWT is most severe by the governing navigable depth at these locations for the waterborne supply chain. Given the fact that vessel loading rates depend on available navigable depth, this is the main driver of cost effects, because of more trips to transport the same amount of cargo. The fleet is represented by one or just a couple of vessel types, which does not provide inside into how changes in fleet composition or deployment might occur. Thus a good representation of vessel deployment based on the navigable conditions (triggers) is not included in the methods reported in the literature. The applied approaches are applicable to examine most of the impacts on loadings rates, number of trips and transport costs, but ignores changes in fleet composition, additional systemic effects and secondary effects in the supply chain, e.g. terminal occupancies.

To effectively design and evaluate mitigating measures for water level related IWT network performance problems, it is important that:

Table 1
Methods and objectives of research projects.

Research	Methods	Objectives
Jonkeren et al. (2007)	Q-H-relation	transport costs
Van Meijeren and Groen (2010)	BIVAS and TRANSTOOLS	transport costs and port competiveness
Hendrickx and Breemersch (2012)	TRANSTOOLS and NODUS	transport flow & transport costs
Ecorys (2011, 2012)	BIVAS and TRANSTOOLS	transport flows and port competiveness
Van Dorsser (2015)	Q-H-relation	transport costs
Christodoulou et al. (2020)	SOBEK and TRANSTOOLS	transport costs
De Jong (2020b)	SOBEK and BIVAS	transport costs
BMVI (2015)	SOBEK and cost structure model	transport costs and competiveness of IWT

Table 2
Models and application.

Model or application	Pros	Cons
BIVAS	transport coupled with navigable depths	vessel deployment and transport based on historical data
NODUS	includes operational activities and other transport modes	no coupling with navigable depths
TRANSTOOLS	includes different types of transport and cargo	no coupling with navigable depths

1. outputs of hydraulic models that describe the state of the waterways network under various discharge scenarios can (time dependently) be fed into water borne transport models;
2. movement of vessels and filling and emptying of cargo storage facilities are resolved in order to capture systemic effects on the supply chain and (changes in) the cargo transport capacity of the network as a whole; and
3. network performance can be investigated as a function of time, rather than through the navigable conditions at a small number of key bottlenecks under various (stationary) discharge scenarios.

The most important addition to methods previously reported in literature is the resolution of systemic effects of (low) water levels on IWT networks. Or as Christodoulou et al. (2020) remark: “It is important to note that for the inland waterways to work as a system, all parts of the system should operate without disruptions.” To assess the performance of ports and waterways systems, Van Koningsveld et al. (2021) suggest to use the waterborne supply chain as a guiding concept. To analyse water level related supply chain disruptions at corridor scale, the consequences of alternative discharge scenarios have typically been analysed by looking at Q-h relations or water level time series at known bottlenecks. While proven an effective approach for the purpose of many of the studies referenced in our literature review, such approaches break the supply chain philosophy and thus hinder the investigation of system effects. In our research it is proposed to model hydrodynamic behaviour at system scale based on one or multiple discharge scenarios that are input for the SOBEK simulations and subsequently simulate the behaviour of waterborne supply chains (Fig. 2).

3. A novel approach to IWT network performance analysis

In Section 2 it is proposed to model behaviour of the waterborne supply chain based on the derived hydrodynamic conditions of a river. This requires the use of a hydrodynamic package combined with a package that simulates the vessel deployment and the performance of the water borne supply chain. In this section the different components of the proposed method are described.

3.1. *Modelling hydrodynamic behaviour at system scale*

For this paper the package SOBEK 3 version 3.7.16 is used, which is a 1D flow solver that is widely applied in flood forecast modelling, for example. Main arguments for selecting SOBEK for this paper are (1) the existence of a well-calibrated schematisation of the Rhine branches in the Netherlands, and (2) the availability of realistic cross sections to derive information about wet perimeters and flow conveying channel areas. This facilitates the derivation of possible draught that depends on the depth that facilitates the defined fairway width (e.g. 150 m for the Waal). The schematization of the Rhine-branches (Rijkswaterstaat, 2019a) is used to investigate the effects of the low discharge extreme of 2018 on the Rhine transport corridor. This is an existing well calibrated model that is primarily used to derive flood risks related to water levels on the river Waal, but has also been calibrated for medium and low discharges based on the conditions of 2018. In these simulations a time-step of one hour is used and discharge scenarios at Lobith are used for the upstream boundary of the schematization.

3.2. *Modelling transport at system scale*

In the proposed method, instead of using one of the packages mentioned in Section 2, the package OpenCLSim (Van Koningsveld et al., 2020) is used to resolve how the transport of cargo over the network is affected by the state of the network. OpenCLSim is an opensource Python package for complex logistics simulation. Key to managing complex project logistics is to understand how disruptions in one part (or phase) of the project might cascade through several interconnected supply chains to affect the overall project

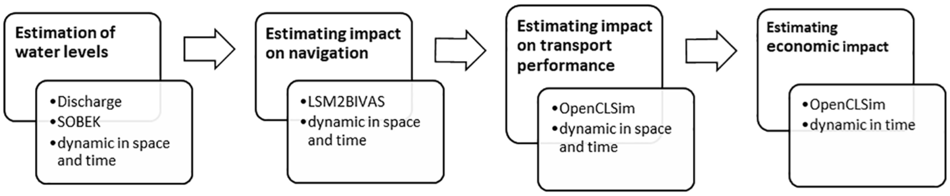


Fig. 2. Schematic overview of proposed methodology.

outcome. The package is built on the concept of Agent Based Simulation (ABS) and Discrete Event Simulation (DES). The aim is to integrate important elements of waterborne supply chains (e.g. vessels, sites, activities and network) into a simulation environment.

3.3. *From flow network to transport graph*

To couple hydrodynamic simulations (i.c. SOBEK) with logistic simulations (i.c. OpenCLSim) at transport corridor scale it is needed to (1) convert the flow network from the hydrodynamic simulation to a transport graph, and (2) translate the model's cross section information to allowable loading rates based on the simulated water levels. Properties of the hydrodynamic simulation network (width and depth) are used as attributes in the transport network. The distance between the calculation points along the river is 500 m. The SOBEK schematisation of the 'Rhine branches' covers the river Waal from Lobith (km 876.00) to Hardinxveld (km 961.00) (Fig. 1). To construct a full transport connection between Rotterdam and Duisburg the trajectories 'Rotterdam - Hardinxveld' and 'Lobith – Duisburg' are added to the network. The navigable depth for the stretch between Rotterdam and Hardinxveld is assumed to be equal to the navigable depth at Hardinxveld. For the section near Rotterdam this seems to be a reasonable assumption, since from practice it is known that no drought related depth restrictions occur on that part of the network. The navigable depth at Lobith is applied as navigable depth for the network from Lobith to Duisburg. For the section towards Duisburg this clearly is a simplification, but the main known bottleneck at the Rhine upstream of Lobith is located at Kaub. To show that observed phenomena can be resolved, these assumptions for the added river stretches are considered acceptable for now.

3.4. *Cross section information to allowable loading rates*

Water levels are derived from running SOBEK for the discharge scenario measured at Lobith during the summer 2018. The navigable depths are determined along the SOBEK grid by taking the local cross-sectional shape from the SOBEK schematisation and a local minimum width of the fairway.

The 'navigable depth' was determined (Eq. 1) for each cross section, by looking at the distance between the bottom level and vertical level (Eq. 2) at which the 'minimum waterway width' can be fit into that cross section (Mens et al., 2018)(Fig. 3). For the river Waal a minimum waterway width of 150 m is applied. The 'available vessel draught' is equal to the navigable depth minus a minimum Under Keel Clearance (UKC). In general an under keel clearance of 0.3–0.5 m is maintained, but in case of low water periods barge operators are known to accept smaller values in order to load as much cargo as possible (see (Van Dorsser et al., 2020) for an elaborate description). The derived 'available vessel draught' (Eq. 3) determines the loading capacity of the vessels that is applied in the OpenCLSim -package.

$$navigable\ depth = water\ depth - correction \tag{1}$$

$$correction = level(waterway\ width = 150) - bottom\ level \tag{2}$$

$$available\ vessel\ draught = navigable\ depth - UKC \tag{3}$$

3.5. *Vessels, terminals and activities*

OpenCLSim extracts loading capacities of the vessel from the cargo storage at the sea port and calculates the time it takes (1) to load that cargo, (2) to transport that amount of cargo to the target inland port (distance divided by vessel speed), (3) to unload that cargo into the inland port storage facility, and (4) to sail back empty. Then the vessel is available to be loaded again. Fig. 4 illustrates this cycle of discrete events and how they are interconnected. The cycle repeats until a predefined condition is met, e.g. no more cargo left to move, specified stop time reached, etc. In this figure the sequence is already given for the casestudy in Section 4 about the transport of iron and coal between Rotterdam and Duisburg. For other cargo types vessels might be loaded again before sailing back to the origin. Depending on the availability of loading and unloading facilities queues may form. A number of attributes need to be specified at the origin and destination location, for example: transport demand and loading rate at the origin, while for the destination the unloading rate and storage capacity need to be defined. In the simulation the fleet is composed by different types of vessels, each with their own characteristics, e.g. vessel type, loading capacity, minimum and maximum draught, sailing speed full/empty and current position on the network. The vessels sail between the origin and destination location depending on transport demand. The type of vessel that is

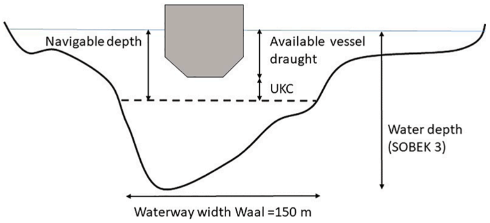


Fig. 3. Link between water depth and available vessel draught.

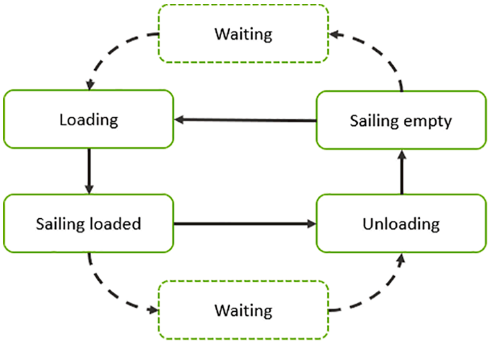
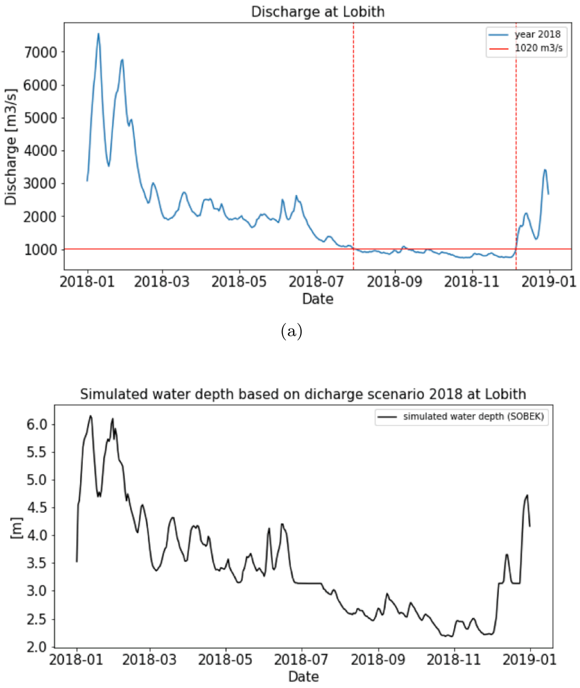


Fig. 4. Sequence of the discrete events in the simulation.

deployed at the origin at a certain point in time, and the loading degree of that vessel, depend on the maximum available draught between the origin and destination in a four day time window (based on the notion that an average trip from Rotterdam to Duisburg takes three/four days (Reguly, 2020). Cargo volumes are monitored at the origin and destination sites and changes are logged after each discrete event. The whereabouts of vessels are also monitored, logging the timestamp (start/stop), geographical position (start/stop) and specific activity (sailing/(un) loading/waiting) for each discrete event for each individual vessel.

4. Case study Inland Waterway Transport on the river Rhine

A case study is discussed to provide the proof of concept of the method for cascading effects for the waterborne supply of dry bulk (e.g. iron ore and coal during the period of prolongated low discharges of 2018 for the corridor at the river Rhine between the seaport of Rotterdam and the inlandport of Duisburg (see Fig. 1). In the area of Duisburg large factories are situated that depend on the supply of these resources. The corridor was chosen for three reasons. First at this corridor the transport of dry bulk to Duisburg is mainly executed by 6-barge push convoys. Transport by these large push convoys has a large share of the total transport volume (De Jong, 2020a). Secondly, the large barge-push vessels have the largest draught (4.0 m) and are most sensitive for low available sailing depths (Marchand et al., 1988). Finally, data of fleet composition and model-schematizations of the Rhine in the Netherlands were available and provided by Rijkswaterstaat.



(a)

(b)

Fig. 5. (a) Daily river discharges at Lobith for 2018 (data provided by Rijkswaterstaat,2019), (b) Simulated minimum water depth at the river as derived using SOBEK.

The daily measured discharge data at Lobith from 2018 is used to analyse the cascading of effects during the prolonged drought. The discharge data are applied at the model's upstream boundary (see Fig. 5a). At the downstream boundaries a varying water level is imposed, based on measured data from 2018. The dry period, defined as the period where discharge levels are below the Agreed Low River discharge (ALR) which is set at 1020 m^3/s, is marked by the two vertical dotted lines. In the beginning of September the values exceed the ALR for a couple of days. Given the discharge data from 2018 the water depths over the total length of the Waal are derived using SOBEK. Fig. 5b shows the simulated daily minimum water depth on this trajectory.

Based on the scope of the casestudy the following considerations are applied to the vessels implemented in OpenCLSim, version 1.0.0.:

- A fixed fleet is used in the simulation that consists of four main vessel classes that are commonly used for the transport of iron and coals (Port of Rotterdam, 2016).
- The number of vessels for each of these four classes, as derived from the BIVAS-IVS-data, is indicated between parentheses.
- The draught of the vessels used in the simulations is given in Table 3.

  The vessels are:
  1. 6-barge push tow concoys (10);
  2. 4- and 2-barge push tow convoys (10);
  3. Rhine vessels (15); and
  4. Coupled barges (20).
- The loading degree is determined based on the available draught (as derived from the SOBEK results) and a linear draught-loading relation based on the measurements letters for a representative barge for the Ruhrort-market and the descriptions according to Van Dorsser (2015).
- The vessel speeds are derived from calculations by Backer van Ommeren (2011): an empty sailing speed of 4.5 m/s is used, while the vessel speed is 2.25 m/s when sailing fully loaded.
- The storage capacities at the origin and destination are 50 and 60 million tons respectively.

4.1. *Changes in number of trips, transported volume and costs*

In this section the results of the BIVAS-IVS-data (Rijkswaterstaat, 2020) analysis (dashed line) of 2018 are compared to the model results of our proposed method (solid line). It is shown for the weekly averaged number of trips (Fig. 6a) and the weekly averaged transported weight (Fig. 6b). The simulated weekly averaged costs are presented in Fig. 6c. The data and the model results show the cumulative values of the four vessel types described in Table 3.

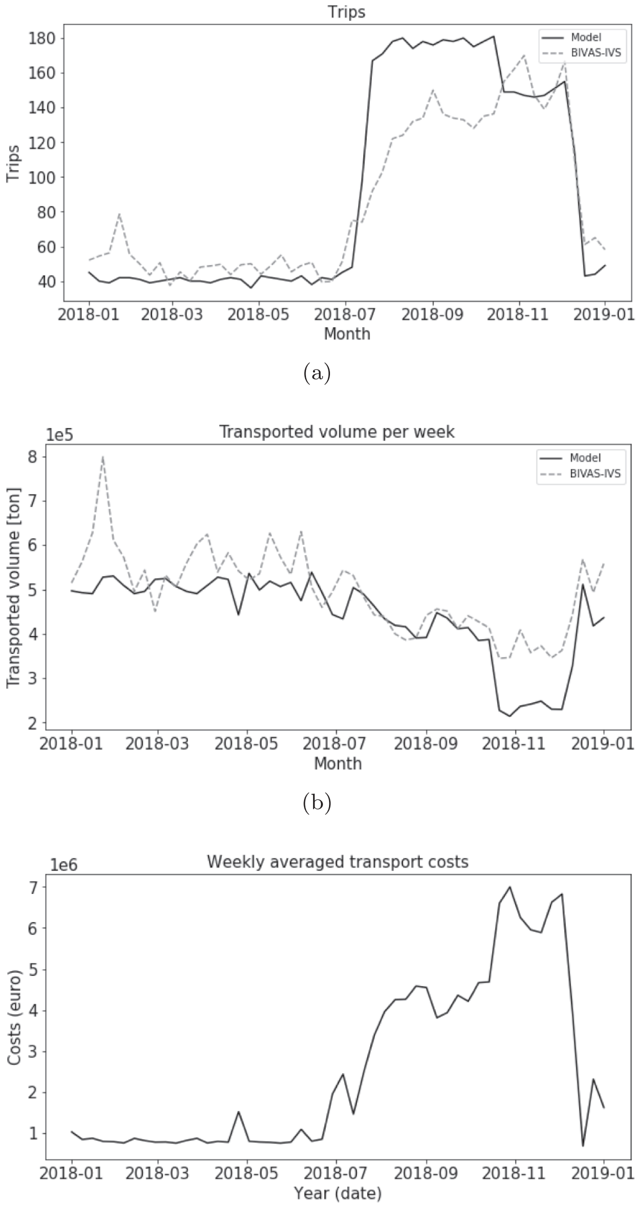
In Fig. 6a the data shows a gradual increase during the low discharges from approximately 40 trips to 150 trips. In comparison to the normal navigation conditions for which vessels can sail fully loaded, during the drought period over three times more trips are required. During the drought the data shows two distinct periods. The first one indicates an average of approximately 130 trips per week, while the second smaller period is characterized by an average of approximately 150 trips per week. In panel A it is observed that the model results are quite similar to the data, but also shows specific differences. The start and the end of the drought are similar and the two periods can be identified in the model results. At the beginning of the drought the modelled number of trips shows a steeper increase than the date and in the first period of the drought the number of trips is higher. In the second period of the drought the number of trips in the data and in the model results are comparable to each other. In Fig. 6b the data (dashed line) shows a gradual decrease of 100.000 ton of the weekly averaged transported weight between normal conditions and the drought. After the decrease a stable phase can be identified, although a clear distinction of two periods as observed in panel A for the number of trips is not shown. Fig. 6c shows the model results of the transport costs. The results show two phases consisting of a gradual increase from one million to four million euros, followed by a quite stable phase between six and seven million euros. The start and end dates of the two phases are similiar to those identified in panel A and B. Although differences are observed, it is promising to see that, even with the highly simplified settings used to run the SOBEK and OpenCLSim packages in this case, the increased number of trips and decrease in transported volume show quite similar patterns compared to the observed BIVAS-IVS-data.

4.2. *Changes in fleet composition and fleet occupancy*

An analysis of the dataset (Rijkswaterstaat, 2020) was executed to observe specific changes in the deployment of the different vessel types, e.g. 6-barge push tow concoys, 4- and 2-barge push tow convoys, Rhine vessels and Coupled barges, used for bulk transport

Table 3
Vessel draughts.

Vessel type	maximum draught (fully loaded) [m]
six barge push tow convoy	4.0
four and two barge push tow convoy	4.0
Rhinevessel	3.5
Coupled barges	4.0



(a)

(b)

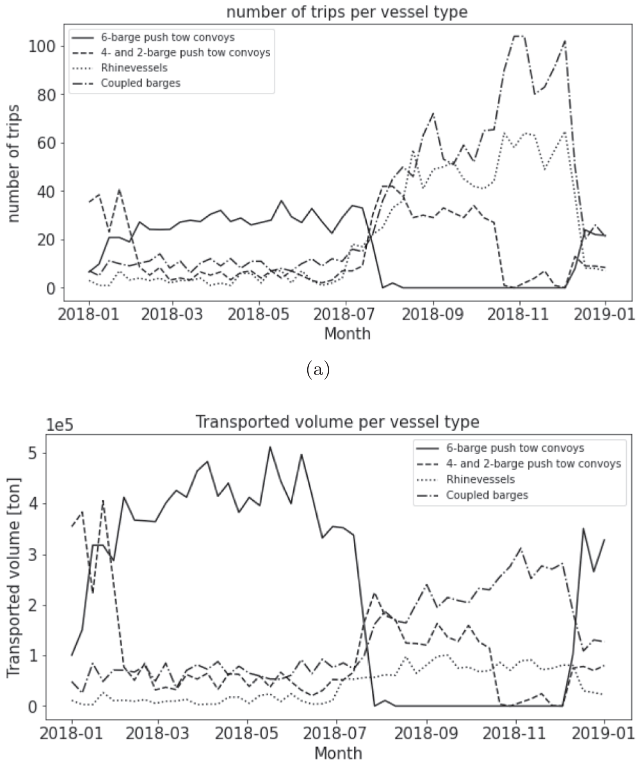
(c)

Fig. 6. Number of trips (a), transported volume (b) and costs (c).

between Rotterdam and Duisburg. It demonstrates that the active fleet composition does not remain constant with changing water levels and the duration of a certain river discharge. Fig. 7a and Fig. 7b show the contribution of the separate vessel classes to the number of trips and transported weight.

It is observed that the deployment of 6-barge convoys stops quickly after the start of the drought and is taken over by the deployment of the smaller 4- and 2-barge convoys. Other compensation of capacity is created by the deployment of Rhine vessels and Coupled barges. The results support the assumption of Marchand et al. (1988) that large barge convoys are most sensitive to shallow water depths, because they make optimal use of the available draught. In periods with low available draughts the deployment of this type of vessels will decrease, because the draught of the push convoys is larger than the available draught. Regulations (MTPWWM, 2018) also prescribe that for low water levels 6-barge convoys are not allowed to sail along the river Rhine. The shift in deployment of vessel classes is observed in Fig. 7a and Fig. 7b. The change in fleet composition is clearly important and not resolved by assuming representative vessel classes for IWT as it was done in several publications reported in our literature review. The risk of severe droughts is different for the several vessel classes and important to understand for the design of mitigation strategies.

Accommodating an increasing number of trips with a fixed number of available ships will likely lead to an increased fleet occu-



(a)

(b)

Fig. 7. Number of trips (a) and transported volume (b) in 2018 for the four vessel classes.

pancy. Fig. 8 shows the simulated weekly fleet occupancies per vessel class. A clear shift is observed during the dry period and daily occupancy rates can be significantly higher, occasionally approaching levels near 80% for the Rhine vessels and Coupled barges towards the end of the drought (not shown in the figure). After the drought the occupancies take normal values as before. In the simulation the number of terminals is set at six berths and this maximizes the number of vessels that can be deployed or loaded.

4.3. Increased congestion in sea ports by reduced loading rates and increased trip numbers

Most literature on the effects of waterlevels on IWT focuses on known bottlenecks in the higher parts of the river network. Via reduced loading rates for a selection of vessel classes economic impacts are assessed. The systemic approach proposed here keeps track of cargo volumes and vessel movements as the drought develops. subSection 4.1 shows that reduced 'available vessel draughts' trigger reduced loading rates and consequently an increased number of trips. subSection 4.2 adds to that there are significant changes in the fleet composition that also affect the network performance. In a systemic approach it seems logical that when more trips are needed to move the same amount of cargo, this must mean that the arrival rate at IWT terminals in sea ports such as the Port of Rotterdam should increase. Of course the inland vessels load less cargo, so the loading time should probably be reduced. But the time needed for mooring/unmooring likely will be unaffected. As a consequence, an increase in the number of trips, should also result in a larger berth

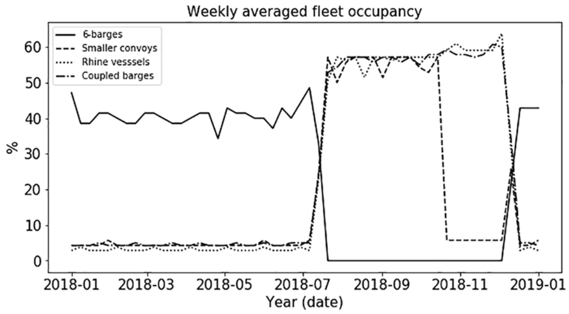


Fig. 8. Weekly averaged fleet occupancy per vessel class.

occupancy. Typically when berth occupancies increase, queue formation is likely to increase. Fig. 9 shows the simulated number of daily arrivals at the origin location in our case study. This number triples during the drought, but at the end drops back to the values before the dry period.

These phenomena have been observed in sea ports. An example is the number of arrivals at the dry bulk terminals at the Port of Rotterdam, as visualised in Fig. 10 (grey). It shows observed numbers from Automatic Identification System (AIS) data of arrivals for different periods of the years 2017, 2018 and 2019 for the total dry bulk fleet. In dry periods of 2017 and 2018, a significant increase of arrivals can be observed compared to the other periods. The amount of arrivals is 1.5–2 times higher during the dry periods than under more common conditions. As comparison to this data the simulated results of the casestudy (Fig. 9) are added in black columns. The higher ratio in our casestudy might be explained by the fact that in the simulation already an overestimation of vessel trips is made (Fig. 6a).

Analysis of the data provided by the Port of Rotterdam furthermore shows a drop in the total time that vessels were in the port area during the dry period of 2018. This drop is likely linked to the fact that reduced cargo volumes would have affected the duration of the (un) loading operations. Unfortunately, the detailed underlying data are confidential and cannot be shared.

4.4. The dynamic response of transport performance during changing water levels

Current literature describes the effects of reduced waterlevels on IWT by considering bottlenecks, and taking reduced loading rates as the primary aspect influencing the cost function. Fig. 11 shows the transported volume of cargo, as derived from the IVS data-set of 2018, projected over the discharge levels at Lobith in 2018. As defined in subSection 4.1, the drought lasted from 1/8/2018 to 5/12/2018, but is characterized by two periods in terms of the river discharge. A continous average discharge of around 1000 m^3/s occurred in August and September, while lower values were recorded in the months October and November. As a response, the IVS-data shows a reduction of around 38% percent of the transported volume in the first period of the drought and a further decrease to 50% in the second period. As discussed in subSection 4.3 the deployment of 6-barge convoys during droughts stops, while single motor vessels and other coupled barges or vessels will take over. Based on the IVS-data it is shown that this does not balance the loss of transport volume by the stop of operation of 6-barge convoys.

The seperate deployment of the four vessel types in 2018 is shown in Fig. 12a, Fig. 12b, Fig. 12c and Fig. 12d.

In the individual panels an comparison is shown between the data and the model results. The deployment (start and end) of the vessels during the drought are similar for all the vessel types. For the 6-, 4- and 2- barge push tow convoys the model and results are comparable. For Rhine vessels and coupled barges the IVS-data shows a gradual increase while an instantaneous increase is observed for the model. This is likely caused by the fact that a clear threshold value of the ‘available vessel draught’ is defined below which the model stops the deployment of push-tow convoys. Exceedance of this threshold value immediately initiates the deployment of other type of vessels with a smaller capacity. In practice this process was probably more gradual. Shipping companies need time to arrange the deployment and hiring of other vessels or barges. The model results show opposite behavior during the dry period compared to the data; increasing respectively decreasing. The difference might be explained by the fact that in the model a maximum amount of cargo can be transported by the different vessel classes for ‘available vessel draughts’, while in practice barge operators are known to have pushed the amount of cargo that would be taken on board to optimize the loading capacity during dry periods. It was visually observed in practice that multiple barges were put alongside a number of available motorvessels instead of the normal push-boats (Van ’t Verlaat, 2019). The above explanation shows that changes in the fleet composition are important to derive proper estimates for the effects of lowering water levels. It provides insight into the exposure to the different vessel classes and the potential risk.

4.5. Storage capacity at destination

As mentioned in Section 1 one of the cascading effects is on storage capacity that ensures operation of industrial processes. In Fig. 13 the computed storage volume is shown at the destination (solid line) compared to the volume that has been transported based on the BIVAS-IVS-data (dashed line) of 2018 by the four vessel types (real data of the storage volumes in Duisburg was not available). During the second phase of the drought a decrease of the simulated filling rate is observed. This trend is not shown clearly in the measured data.

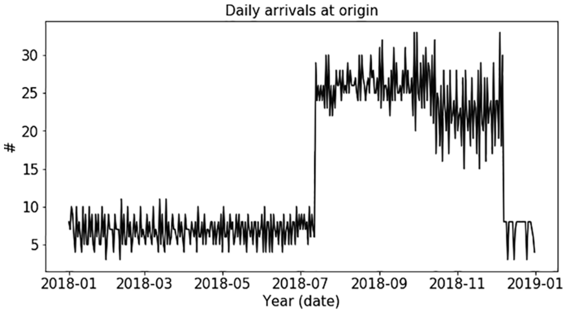


Fig. 9. Simulated number of arrivals at the terminals at the origin, Rotterdam.

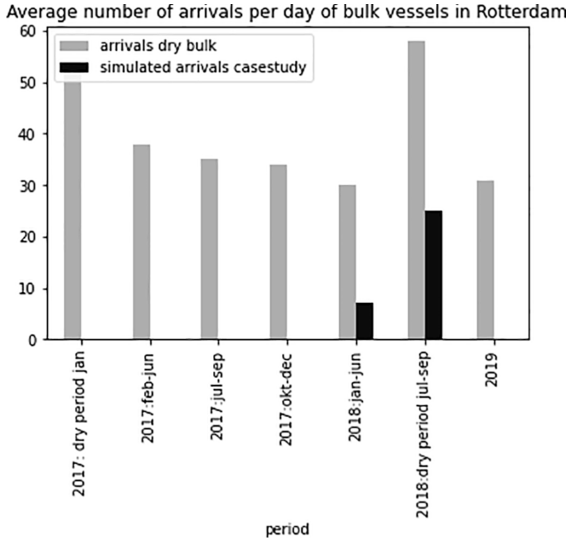


Fig. 10. Number of arrivals at the dry bulk terminals in the Port of Rotterdam (grey)(numbers provided by Port of Rotterdam (2020)) combined with simulated arrivals at origin in the casestudy (black).

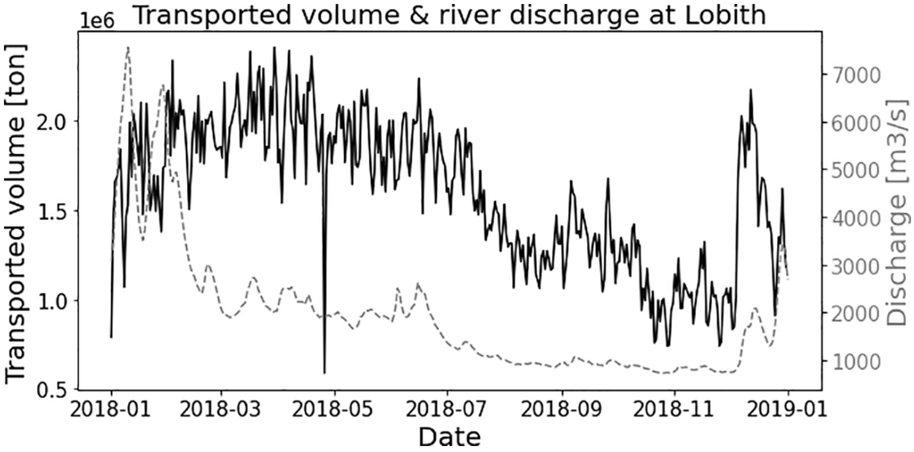


Fig. 11. Transported volume in ton (IVS-data) projected over discharge levels at Lobith.

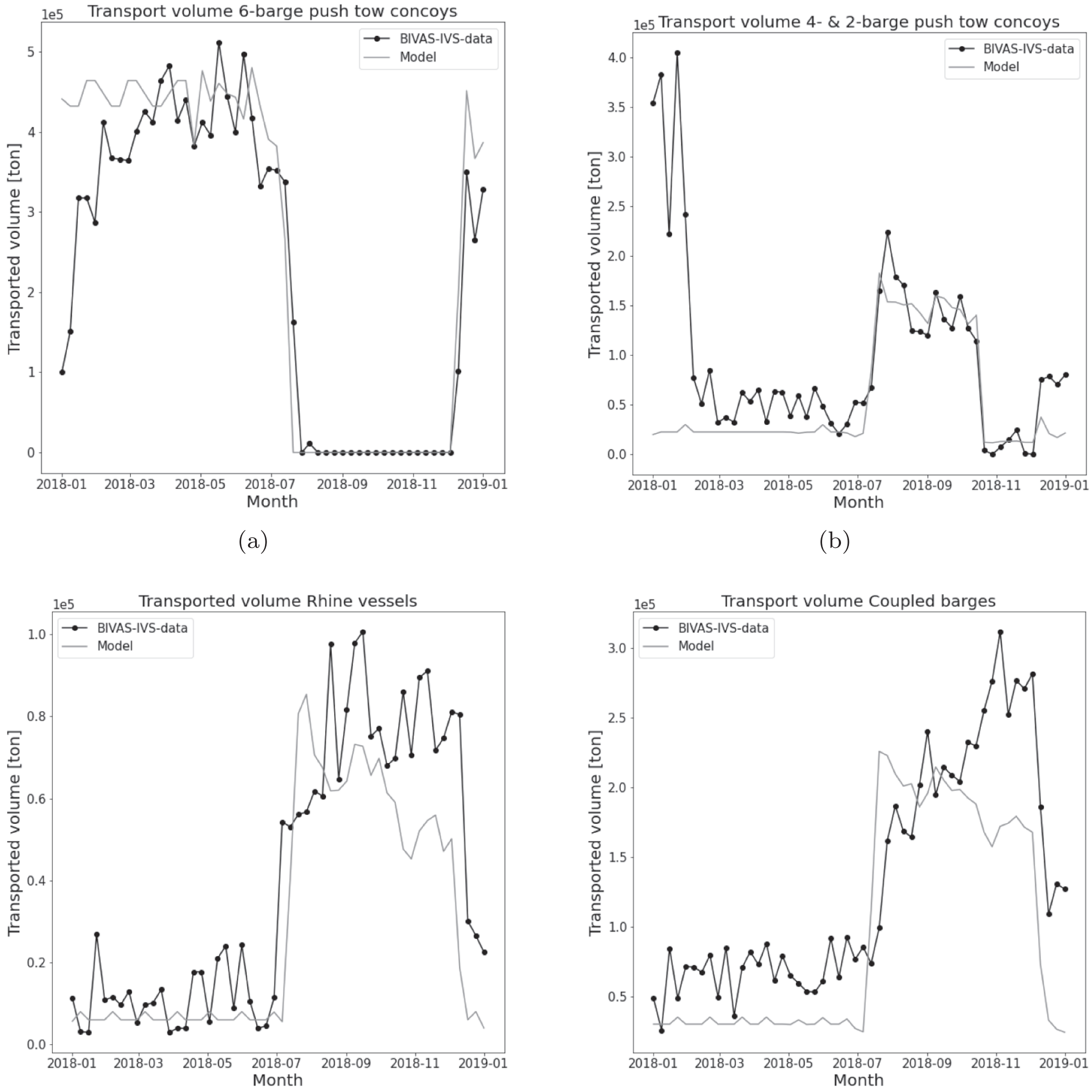
As demonstrated in Fig. 12c and Fig. 12d the compensated transport volume by the Rhine vessels and coupled convoys was already underestimated by the simulation. Although the simulation is an underestimation, it shows that the proposed method is capable to model the filling rate of the stockpile at the destination. In practice, the decline of the daily filling rate might cause disruptions in industrial operation if this is lower than the volume required for those processes on a day for a longer period.

5. Discussion

This paper reviewed the state of the art in assessing the effects of water levels on IWT network performance. A knowledge gap was identified in literature and a novel method was proposed to explicitly resolve shipping response to low discharge events and IWT network performance, using a supply chain approach.

While some interesting phenomena were covered in this paper that appear to be lacking in the current literature, it has to be acknowledged that:

- Daily navigable depths are coupled to the network, but only for the river Waal between Lobith and Hardinxveld. Simulation of the navigablility between Lobith and Duisburg could reveal other bottlenecks and improve the performance analysis of the waterborne supply chain;
- In the novel method triggers are defined for vessel deployment during prolonged drought. In Section 4 it was demonstrated that these were identical to IVS-data. Based on the results in this paper implementation of high water situations can be implemented in



(a) (b)

(c) (d)

Fig. 12. Response in weekly averaged transported weight [ton] per vessel type (a) 6-barge push units, (b) 4 and 2 barge push units, (c) Rhine vessels and (d) Coupled barges.

future simulations e.g. according the regulations (MTPWWM, 2018) 6-barge push units are not allowed to navigate above a certain water level measured at Lobith and Ruhrort;

- The model reproduces similar start and stop moments for the deployment of the vessels, but the instantaneous increase of number of vessels and trips does not match the gradual increase observed in the data. A correction needs to be made on the increase rate of vessel deployment in future model developement;
- At the end of the dry period the model shows a smaller total transported volume. A closer look at the seperate vessel classes shows that this is caused by a higher transport volume for the Rhine vessels and coupled barges. In future work we have to redefine the transport capacity of the individual vessel types;
- In this paper model input parameters and the model results are based on compared to IVS-data. AIS-data is more accurate regarding vessel speeds (Yun, 2021) and number trips. Validation of input parameters and comparison with AIS-data can improve the method;
- It was demonstrated that transport volumes were taken over by motorvessels and coupled barges. In contrast to our simulations, during the drought an increase of transport volumes by these type of vessels is observed in the IVS-data. A thorough analysis of this observation is recommended to understand behaviour of barge operators during sustained low water levels;
- The novel method is mainly focused on the transport of dry bulk (iron and coal) between Rotterdam and Duisburg. Implementation of cargo types liquid bulk and containers improves the applicability of the method;

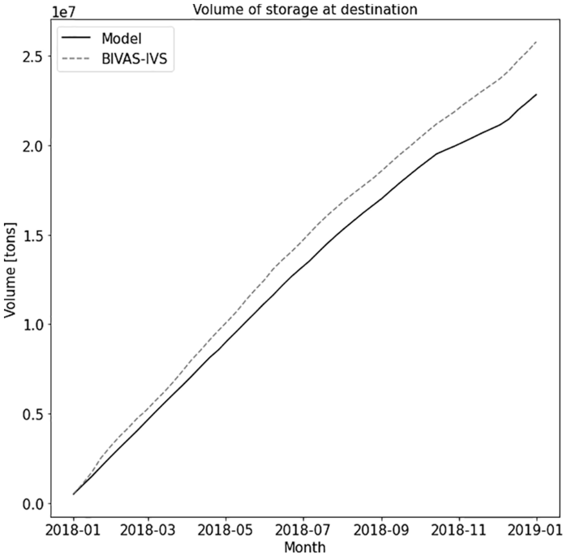


Fig. 13. Storage capacity at destination.

- The presented sequence of discrete events (Fig. 4) assumes a one-direction cargo flow upstream and sailing empty back without stops. For dry bulk this seems to be a valid assumption, but regarding liquid bulk and containers adjustments on this sequence has to be made. Mooring and unmooring are not defined as separate activities; their effect on the total trip time is negligible, but they may affect port operations at the terminal if the number of arrivals increases during droughts.

6. Conclusions

In this paper it was shown that cascading effects of sustained low water on inland shipping can be assessed by looking beyond depth-bottlenecks and steady state analyses. The relevance and benefits of such an approach was shown for behaviours observed during the drought of 2018. An exploration of the IVS-data was executed to examine how vessel deployment for dry bulk transport between Rotterdam and Duisburg was affected during low discharge periods. Identified phenomena are presented that are not resolved in other approaches in current literature. The proposed novel method shows promising results of this first coarse analysis. Simplified fleet and cargo demands simulates similar results for number of vessel trips and transported volumes compared to BIVAS-IVS observations. These findings suggest that water level changes have a significant impact on fleet composition, occupancy and arrivals at origin or destination. By incorporating changes in the fleet composition, cascading effects on the number of trips, the transported amount of cargo and the economic impact can be resolved properly. This shows that a systemic approach has added value to analyse cascading effects and the assessment of climate related risks. The results demonstrate that improvement on high water triggers, the sequence of activities and loading capacity of vessels for future development is required. This paper contributes to current literature on adaptation and climate risk management by providing a systemic and time dependent approach that is capable to properly represent observed cascading effects and applicable to evaluate and compare sensible measures for mitigation.

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.

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