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The effect of low water on loading capacity of inland ships

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Prolonged periods of drought affect river discharges and cause water levels and available water depth to drop for extended periods of time. Low water depth has a major impact on the loading capacity of inland ships, and as a consequence on the transport capacity of the overall waterborne supply chain. Individual ship owners have detailed knowledge on how much the draught of their ship and the associated cargo weight should be reduced to adapt to low water. These parameters are even adjusted as a function of environmental circumstances (e.g. composition of the riverbed) and type of cargo. This detailed knowledge is, however, not accessible at an aggregated level to assess the effects on the overall transport capacity of an inland waterway transport network. Based on a range of field observations and information collected from individual ships, this article introduces a general model to define the effect of low water constraints on the deadweight and payload of inland ships, for which only the type, length, and beam of the vessel serve as mandatory input. Availability of a general model of the capacity reducing effect of lowered water depth is important for the design and operation of robust transport chains on the one hand, and for the optimisation of fairway maintenance and long-term infrastructure development on the other.

Keywords: *inland shipping, water depth, draft, deadweight, payload.*

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1. Introduction

For road and rail transport the loading capacity of individual transport units does not change over time. This does not hold for inland shipping, where, especially on free-flowing rivers, the loading capacity is constrained by available water depth (EICB, 2011; Van Dorsser, 2016; Hekkenberg, van Dorsser and Schweighofer, 2017). The loading capacity or deadweight is measured in tonnes and consists of the payload and the weight of the ship's consumables, which are mainly fuel and water. The maximum loading capacity is reached at the design draft. This is the maximum draft (or load line) up to which a ship is legally allowed to load. There is a direct relation between the draft and the loading capacity of ships, as a reduced draft requires a reduced displacement and thus a reduced deadweight. During low water periods the deadweight of individual ships needs to be substantially reduced. The effect on overall fleet capacity, however, is partly mitigated by the sector through sailing more hours, increasing engine power to sail faster on stretches where sufficient water depth is available, and utilising reserve capacity. There are, nevertheless, limits to how much the sector can compensate, and the impact on shipping costs for the owner of the cargo can be excessive due to much higher freight rates (CCNR, 2019). Moreover, at a sufficiently low discharge volume, sailing is no longer possible (Riquelme Solar, 2012). This was also partly the case on the Rhine during the extreme drought of 2018 (Mainport, 2018).

Effects of low water on inland shipping have been addressed by Jonkeren and Rietveld (2009), and Jonkeren (2009). Although these studies provide relevant insight in the economic effects of low water for the Rhine, they do not utilize the physical relation between the available water depth and the deadweight of inland ships. Rather, they apply a linear regression model in which effects on prices and load factors are assessed by nine dummy variables for different water depths and four dummy variables for different ship sizes, assuming that the effect of low water on the load factor is independent of the concerned ship type, its self-weight (or lightweight), and its specific dimensions (including the minimum and maximum loading draft). We expect that their approach can be improved by taking physical ship properties into account. Moreover, to improve logistics operations in periods of extreme drought and to secure the robustness of the overall supply chain better understanding of the physical relation between available water depth and inland ship capacity is essential. This is also the case for waterway managers to optimise guaranteed water depths in relation to the cost of maintenance. These issues are already important in absence of climate change, but gain further relevance in the light of efforts to adapt inland waterway transport to the needs of changing climate conditions (Krekt et al., 2011; Turpijn and Weekhout, 2011; Hendrickx and Breemersch, 2012; Beuthe et al., 2014; and Hiemstra, 2019).

In practice the relation between water depth, loading draft, and the ship's deadweight is well known by individual ships. In fact, it is stated in the official loading or tonnage certificate. However, an accurate model that can be applied by policy analysts and researchers to assess the impact of low water on ship capacity in general has not been published in scientific literature. Attempts to address the physical relation between the available water depth and the ship's deadweight were undertaken by Bosschieter (2005), Riquelme Solar (2012), Hekkenberg (2013), and Van Dorsser (2015). Furthermore, Rijkswaterstaat, the Dutch national infrastructure provider for road and waterway infrastructure, uses the BIVAS model to assess the effects of reduced water depth.

Bosschieter (2005) used 'average' ship data from Roelse (2002) to estimate the effect of low water conditions on the deadweight for ships of various sizes, assuming fixed block coefficients (i.e. submerged volume divided by the product of length, beam, and draft) irrespective of the draft, which is an approximation because the block coefficient increases with increasing draft. She distinguished between self-propelled ships and dumb barges and recognised the relation between loading draft and deadweight as well as the fact that this relation differs for ships of different dimensions. However, the applied relations were not calibrated against real ship data. Moreover, no distinction was made for various types of ships (i.e. dry cargo, containers, and liquid bulk) nor for differences between single and double hull ships. Bosschieter has also not included a required safety margin against grounding, or under keel clearance, and set the ship draft equal to the water depth. While reasonable in the context of assessing normal low water effects, these simplifications have substantial impact on the estimated deadweight in extreme low water.

Riquelme Solar (2012) searched for tipping points from whereon sailing is no longer possible. She found, on the basis of three interviews with inland shipping companies, a minimum draft of 1.40 meter for smaller ships and a minimum draft of up to 1.80 meter for pusher tugs, for which the pusher unit is deeper drafted than the dumb barges it pushes. However, inland shipping operations during the 2018 drought, indicate that smaller drafts have been applied in practice. This suggests that these numbers for minimum required draft need to be reconsidered.

BIVAS is developed by Rijkswaterstaat, part of the Dutch ministry of Infrastructure and Water Management, to analyse the traffic of inland ships on the network (Rijkswaterstaat, 2018). The main objective of the tool is to assign cargo to ships and ships to routes taking into account the optimal, most cost effective, transport solution from one location to another given a certain traffic scenario and available water depths (Meijeren et al, 2011). In case no optimum route is found as a result of low water conditions, the ship's load is reduced. This happens when the water depth is smaller than the draft of the ship plus the required under keel clearance. The capacity reduction goes on until a certain threshold value is reached after which sailing is assumed no longer to be possible. Being developed as a network allocation model, the modelling of low water effects on ship capacity is basic. Adjustments in the capacity of inland ships are based on a fixed tonnage reduction per cm water reduction that depends on the ship's class. This approach is similar to the one used by Bosschieter (2005) that assumes a fixed block coefficient over the entire draft range. BIVAS does include an under keel clearance for which it distinguishes between an absolute under keel clearance of 30 cm on rivers sections and a relative under keel clearance of 25% of the draft on canals. The tipping point from whereon sailing operations are no longer deemed possible is user-defined. The default value was reported to be set at 50% of the maximum load by Meijeren et al. (2011) and at 67% of the maximum load by Prins (2017). The modelling approach applied in BIVAS provides accurate estimates near design draft but becomes gradually less accurate at lower drafts, especially during more extreme low water conditions. The reduced accuracy at lower draft has three reasons. First, estimates become less accurate at low draft because BIVAS ignores the fact that the tonnage reduction per cm of reduced draft becomes smaller towards the keel due to the shape of the ship. Second, the estimate of the point from whereon sailing is no longer possible seems to be based on an assumed value rather than on actual ship data. Third, effects are assumed to be similar for all ships of a certain size class regardless of their type (e.g. dry cargo, container, tanker) whereas in reality the deadweight of ships of a different type will differ due to differences in lightweight construction (i.e. weight of empty ship, which may e.g. be substantially different for identically sized dry bulk and tank ships). This implies that BIVAS provides acceptable estimates at normal low water conditions but is less accurate for assessing effects during extreme low water conditions.

Hekkenberg (2013) based the relation between the ship's draft and deadweight on a parametric ship design model, that estimates the hull shape, lightweight and deadweight of the ship as a function of its length, beam, and draft. In theory, this resolves the issues that the per cm tonnage reduction becomes smaller towards the keel. There are, however, a few drawbacks. First, it is quite cumbersome to create a new design for each ship that needs to be evaluated. Second, the model applies a simplified hull shape for which the results may still differ from data obtained from real ships.

Van Dorsser (2015) applied real ship data from the tonnage certificates of two inland ships to assess the effect of reduced water depth on loading capacity. He assumed these two vessels to be representative for the Rhine and applied a fixed under keel clearance of 30 cm to define the maximum loading draft. Compared to others the benefit of this approach is that real ship data are applied, providing more accurate estimates of the capacity reducing effect of low water. However, the fact that only two distinct container ships were considered makes this approach insufficiently generic. In addition, the use of a fixed under keel clearance is not fully in line with what happens in practice. In practice the applied under keel clearance depends on the type of the ship and its cargo, the properties of the riverbed (rock or sand), and the risk attitude of the ship captain. The under keel clearance can be defined more accurately when these factors are taken into account.

To improve the generic assessment of the effects of low water depth on inland ship capacity we need: (1) better insight in the applied under keel clearance; and (2) a general model for assessing low water impact accurately and specifically for inland ships of different type and size. This paper addresses both gaps by incorporating information on the minimum required sailing draft and the required under keel clearance (that has been obtained from the sector for the extreme drought of 2018), and by systematically analysing the loading certificates of 124 inland ships, for which data was also obtained from the sector. The model output has been validated with data from an additional independent set of 33 ships of different size and type.

The paper continues as follows. Section 2 addresses the overall model structure for which the individual components are further discussed and developed throughout this paper. Section 3 continues with the first building block that concerns a discussion on the applied under keel clearance and the minimum draft required to continue inland shipping operations on the Rhine. Section 4 addresses how loading certificates describe the relation between the draft and deadweight of individual ships and discusses the ship data that was used to develop the model. Section 5 describes the development of a general model to estimate the relative changes in deadweight of inland ships at various drafts. Section 6 presents three supporting models that allow estimation of unknown parameters. Section 7 addresses the validation of the models on their own and in combination. Section 8 addresses the application of the proposed modelling approach. Conclusions and further discussion follow in Section 9.

2. The proposed modelling approach

The proposed modelling approach consist of a table stating the minimum required draft and applied under keel clearance for ships of various type and size (Table 1), and a general model (Table 3) with three supporting models (Table 4, 5, and 6) to assess the effects of reduced water depth on the deadweight of inland ships. The modelling approach requires only a few basic parameters as input. The parameters required by the general model are the actual draft (i.e. the actual water depth minus the applied under keel clearance*), the empty draft*, the design draft*, and the design capacity*. In case items indicated with an * are unknown estimates can be made based on the length, beam, ship type, hull type, water depth, riverbed (sand or rock), and the risk attitude of captain (see Figure 1). The proposed approach enables a more accurate estimate of the impact of low water depth on ship loading capacity, which helps to improve simulations of the overall capacity of the inland waterway transport network under various scenarios, including climate change.

The general model presented in Table 3 defines the relative changes in loading capacity (i.e. deadweight) at an actual loading draft compared to a predefined reference capacity at an arbitrary baseline draft of 2.50 m. This baseline draft serves as reference point in the capacity calculations for which the corresponding deadweight is referred to as the baseline capacity. The approach to define the ship's capacity relative to an arbitrary chosen baseline capacity is counterintuitive as one might expect a model that estimates the absolute tonnage capacity directly form the input parameters. However, the approach suggested in this paper has the major benefit that the input variables are dimensionless and independent of the actual ship dimensions. In fact, the model in Table 3 requires only the empty draft to be known in addition to the actual draft. This makes the model rather general and easy to use.

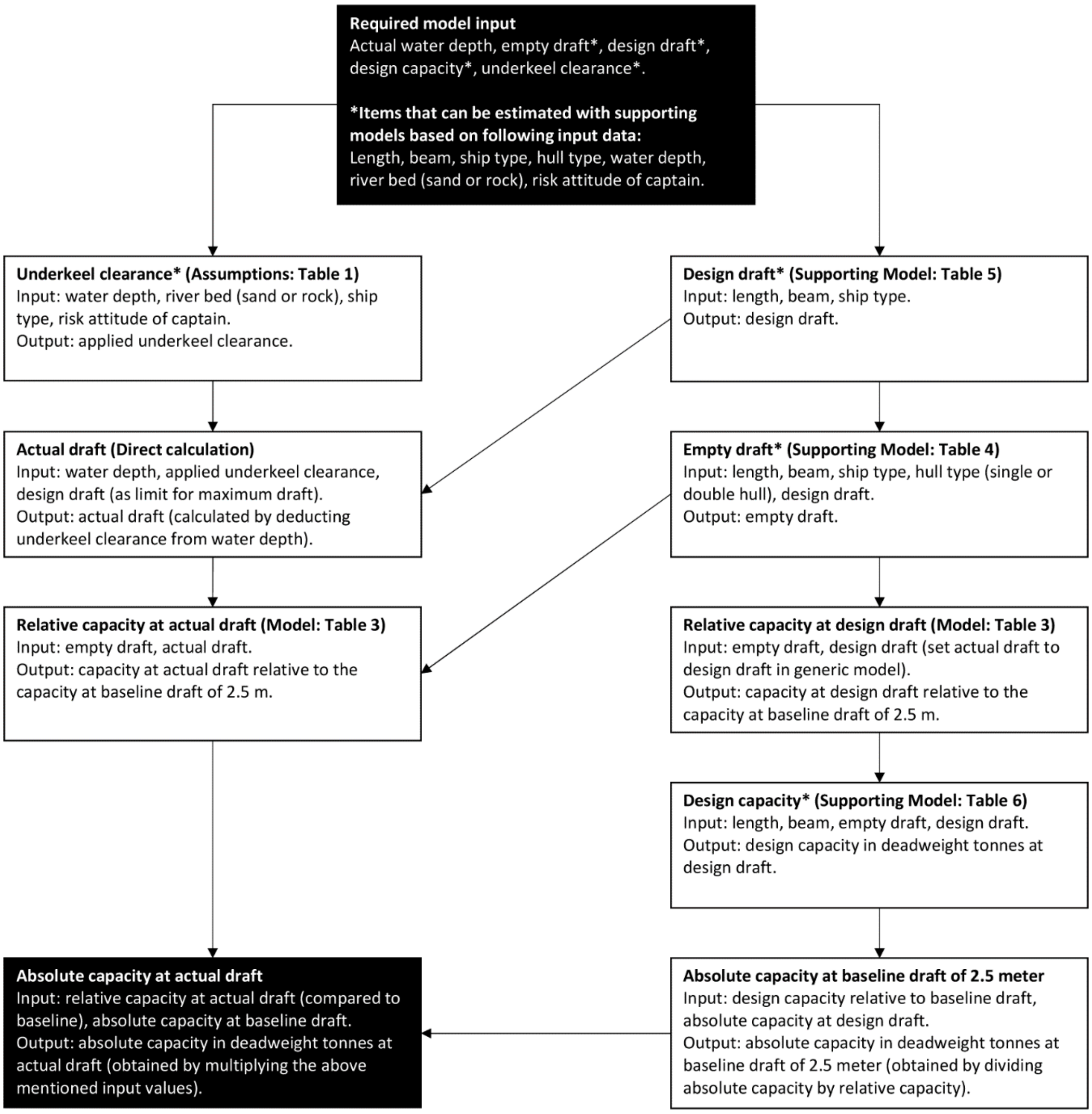


Figure 1. The proposed modelling approach

A complication of the general model in Table 3 is, however, that the empty draft needs to be known by the users, which is usually not the case. To resolve this issue, a supporting model is provided in Table 4, that can be used to estimate the empty loading draft as a function of the ship's length, beam, type (container, tanker, bulk, and dumb barge), hull type (single or double hull), and design draft. In case the design draft is unknown, it can be estimated with a supporting model presented in Table 5. To estimate the absolute capacity in deadweight tonnes rather than as a factor relative to baseline capacity, the absolute capacity needs to be known at a specific draft, for instance at design draft. If the design capacity is unknown, it can be estimated with a third supporting model presented in Table 6.

Once the design draft and corresponding design capacity (i.e. deadweight tonnage at design draft) are known, the baseline capacity can be defined by applying the following two steps: (1) estimate the relative loading capacity factor at design draft compared to the loading capacity at baseline draft by using the model in Table 3, for which the actual draft is set equal to the design draft of the vessel; (2) divide the absolute design capacity by the relative loading capacity factor calculated under step 1. Once the baseline capacity is calculated the capacity at any other draft can subsequently be derived by multiplying the relative loading capacity factor at the concerned draft (i.e. the actual draft in the model) by the absolute capacity at the baseline draft.

3. Water depth and loading draft

Inland ships require a minimum water depth to sail. This minimum water depth depends on the draft required to keep the ship's propeller sufficiently submerged and the minimum under keel clearance that is required to avoid grounding. The following estimates on the minimum required draft for inland ships have been reported in literature:

- Burgers (2005) reports a minimum required draft of 1.70 meter for large pusher barges of ThyssenKrupp Veerhaven B.V.;
- Riquelme Solar (2012) reports a minimum required draft of 1.40 to 1.60 meter for motorships of varying sizes and a minimum required draft of 1.80 to 1.85 meter for pusher barges, which is larger than indicated by Burgers (2005); and
- Van Dorsser (2015) suggests, a minimum draft of 1.50 meter for standard Rhine ships of 110 x 11.4 meter and of 1.60 meter for larger ships of 135 x 14.2 meter.

The standard Rhine ship mentioned by van Dorsser (2015) refers to a Class V ship in the official classification of the Conférence Européenne des Ministres des Transports (CEMT, 1992). The reader is assumed to be familiar with the CEMT-92 classification. If not, a concise overview is provided by Rijkswaterstaat (2011).

The applied under keel clearance depends on the type of cargo shipped (smaller clearance is used for dry bulk than for chemicals), the type of riverbed (smaller margins are applied for sand beds than for rock), and the trim angle of the ship. It is common for loaded inland ships to apply a trim of about 2 to 5 cm over the length of the ship. When sailing upstream the bow of the ship is loaded slightly deeper than the stern to avoid the risk of spinning around when getting grounded. In a similar way the stern is loaded deeper when sailing downstream (van Dorsser, 2015). Usually, a safety margin of about 20 to 40 cm is used against grounding (EICB, 2011). This is measured from the average (or equal) loaded draft without trim and without squat. As discussed, BIVAS applies a minimum under keel clearance of 30 cm at low water conditions and the same value was also applied by van Dorsser (2015). However, especially in extreme low water periods, when freight rates go up dramatically, some ship owners take higher risks and reduce under keel clearance where others stick with more conventional margins. This undercutting of a safe under keel clearance also happened during the 2018 drought, as we understood (in personal communication) that several ships touched the riverbed occasionally, potentially resulting in damage.

To illustrate the risks some inland ship owners are willing to take when rewards are high, let us consider the following two cases. Firstly, it was understood from a Class V tanker captain (in personal communication) that during extreme low water conditions they pumped water from the back to the front of the ship and vice versa to make a way through the critical section in the middle part of the Rhine, that is characterised by pebble stones at the bed. Taking such risks allowed him to remain in operation in a period with exceptionally good rates, while the vast majority of the tanker fleet had already stopped operations at water levels some 30 to 40 cm higher (i.e. corresponding to an under keel clearance of about 30 to 40 cm). Slightly less extreme, it was understood from a Class V container ship captain (in personal communication) that they were able to keep sailing on the river IJssel, that has relatively short sandy shoals, with a loading draft of 1.40 m for a reported least measured water depth of 1.45 m. In his eyes this reflected the limit of what is reasonably possible. When nearing a shoal, the ship's speed is reduced to walking pace to avoid squat and to let the ship slowly glide over the sandy bar. As such, some ship owners are willing to take substantial risks of getting grounded and load to drafts almost identical to the water depth, relying on their experience and trusting on the fact that the ship does not require the full width of the fairway and that larger than guaranteed water depths are usually available when following the deepest path of the fairway (that normally follows the outer bend of the river).

The above descriptions illustrate the more extreme behaviour of some inland ships, that can be lucrative for individual ship owners but are not representative for the entire fleet. In general, most ship owners apply more responsible under keel clearances. Guidelines on safe loading draft that have been suggested by the sector rely on 'good seamanship' to define the under keel clearance, for which they suggest some 20 to 40 cm. These guidelines further indicate that German jurisprudence mentions that 20 cm is considered acceptable for a tanker on a sandy bottom, but unacceptable for a tanker on a rocky bottom (EBM, date unknown). Considering these guidelines and the observation of the tanker captain that most tankers had stopped operations at 30 to 40 cm higher water levels than the level at which he touched the riverbed, we consider it reasonable to assume a default minimum under keel clearance for tankers of 20 cm on a sand bottom and of 30 cm on a rocky bottom. For dry cargo ships and container ships a 10 cm lower margin is considered reasonable.

For pusher barges the actual under keel clearance follows from assessing the water depth in the days prior to 16 October 2018, when Mainport (2018) reported that the operations of all six pusher barges of Thyssenkrupp Veerhaven B.V. had ceased and that the company had hired over 50 motorships (with a lower required draft than the pusher barges) to continue supply by taking the dumb barges aside the hired motorships (Mainport, 2018). In the previous days from 13-10-2018 to 16-10-2018 the minimum guaranteed water depth on the Waal decreased from 2.00 to 1.90 meter (Rijkswaterstaat, 2019). Considering a draft of about 1.70 meter for pusher barges (Burgers, 2005) this implies that the minimum applied under keel clearance was in the order of 20 to 30 cm. Note that we assume Burgers (2005) to provide a more specific estimate of the minimum required draft than Riquelme Solar (2012) as Burgers performed a master thesis study on this topic at Thyssenkrupp Veerhaven B.V., a large inland ship operator. This gave Burgers access to a large amount of data from practice that Riquelme Solar did not have. To assess the effect of low water on inland shipping, the mechanism of taking dumb barges aside self-propelled motorships is relevant, because it implies that the transport capacity of dumb barges in the pusher fleet can be maintained even if their pusher units are forced out of operation. Taking dumb barges aside motorships is costly, but not as costly as shutting down industries.

Requilme Solar (2012) indicated a minimum required draft of about 1.40 to 1.60 meter for motorships. Operational insight from the 2018 low water period enables a refinement of these numbers. Mainport (2018) magazine reported on 16-10-2018, when the water level mark (or 'pegel' in German) at Kaub was only 42 cm, that container operations between Neuss (near Dusseldorf) and Ginsheim-Gustafsburg (upstream of Kaub) had come almost completely to a hold. On this approximately 200 km long trajectory only 5 out of 40 container ships of Contargo were still in business. The 5 ships that still remained in business are presumably the smaller ones. This implies that the majority of the motorships had ceased sailing at a corresponding water depth of approximately 1.54 meter, as calculated for Kaub with Equation 1 (Binnenvaartkennis, 2019).

$$1.90\ \text{m (guaranteed depth)} + 0.42\ \text{m (pegel)} - 0.78\ \text{m (corresponding level)} = 1.54\ \text{m} \tag{1}$$

Container ships on the Rhine are mostly of Class V or higher. Considering a default under keel clearance of about 20 cm it seems that a minimum draft of 1.34 meter is too little to maintain operations. On the other hand, shipping was still continued on the route between Rotterdam and Duisburg (with even larger ships) in the periods from 24-10-2018 to 31-10-2018 and again from 21-11-2018 to 3-12-2018 when reported lowest measured water depths dropped to just 1.60 meter. This suggests that for Class V ships a water depth of 1.40 meter can be regarded as a minimum, though keeping in mind that these ships may sail around the shallowest spots, such that in fact more water depth is available.

Insight in minimum required draft for Class II and III ships is obtained from a barge operator (in personal communication), who indicated that operations were still continued with small ships during the most excessive low water conditions, when the pegel at Kaub dropped to just 25 cm (measured on 22-10-2018). The corresponding water depth for this pegel is only 1.37 meter. Assuming an applied under keel clearance of about 15 to 20 cm these small ships seem to have continued sailing at a draft of approximately 1.20 meter.

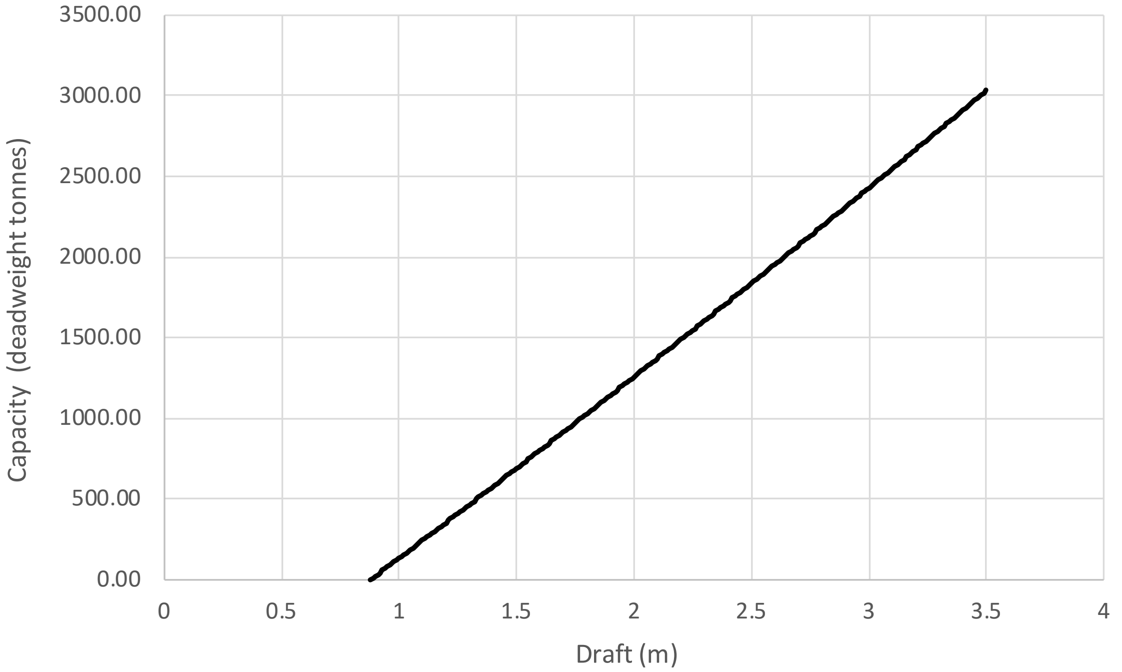
Table 1. Required minimum draft and under keel clearance (UKC) for inland ships

Motorships and pusher barges	Minimum required operational draft	Default UKC (sand bottom)	Default UKC (stone bottom)
Class II & III	1.20 meter	10 cm for dry bulk and containers. 20 cm for tankers and pusher barges.	20 cm for dry bulk and containers. 30 cm for tankers and pusher barges.
Class IV	1.30 meter		
Class V	1.40 meter		
Class VI	1.50 meter		
Pusher barge	1.70 meter		

Based on these samples of information, and recognising the shortfalls in the available data, we propose the following default values, as presented in Table 1, for the minimum required draft and under keel clearance. These values can be used when assessing the impact of low water on the operational performance of inland ships since the combination of a known water depth with a known under keel clearance leads to a known draft. The difference between this draft and a ship's design draft determines the reduction in cargo carrying capacity, as will be discussed in detail in this article. Cargo carrying capacity is a crucial factor in the determination of the operational performance, which is commonly expressed in the number of tonkilometres of transport performed in a given amount of time. Given the shortfalls in the data and to address the differences in the behaviour of ship captains, we recommend considering an uncertainty of ±10 cm on the actual under keel clearance.

4. Draft and loading capacity

To assess the impact during normal low water periods in which ships are able to keep sailing, we need to be able to relate the ship's allowable draft to the tonnage that can be loaded. For each inland ship, the relation between deadweight tonnage and loading draft is reported in the official loading or tonnage certificate of the ship, that assumes an equal loaded draft of the ship (i.e. no trim applied). In reality, however, the equal loaded draft mentioned in the loading certificate cannot always be attained in practice, as empty ships are subject to trim. In fact, the keel at the stern is typically one meter lower than at the front for an empty ship. During low water conditions this trim effect is countered by loading cargo only in the front of the ship to reduce trim. This practice was confirmed in personal conversations with crew members working on board of inland ships during the extreme low water conditions of 2018, who shared their photos showing container ships sailing with containers loaded only in the foremost container bays (i.e. loading spaces) to minimise trim. Despite the occurrence of trim effects in practice, the actual drafts and empty drafts mentioned in the remainder of this paper will always refer to the equal loaded draft (or average draft) and not to the real drafts when taking trim effects into account. A typical example of the deadweight to draft relation for a Class V container ship is indicated in Figure 2.



Source: van Dorsser (2015, p. 265)

Figure 2. *Typical example of a deadweight to draft relation for a 110 x 11.45 m ship*

The relation between tonnage loaded and corresponding draft follows the law of Archimedes, which states that the weight of the loaded ship (including payload and consumables) equals the weight of the displaced volume of water, or the displacement. In fresh water the density of water is almost exactly one tonne per cubic meter, which means that the displaced volume expressed in cubic meters equals the displacement in tonnes. The deadweight tonnage includes the payload and the weight of the ship's consumables, but it excludes the self-weight of the empty ship (i.e. the lightweight). The payload, i.e. the cargo weight that is actually transported, does not include the weight of the consumables, which, based on reference data for 5 inland ships, accounts for approximately 4% to 8% of the of the design deadweight (van Dorsser, 2015). Especially during extreme low water conditions, when only about 10% to 20% of the design deadweight remains, the need for consumables (predominantly fuel and fresh water) can take up a substantial part of the low water deadweight. To increase payload, ship owners can reduce drinking water and fuel supplies to a bare minimum.

To analyse the relation between draft and loading capacity in general, a total of 157 tonnage certificates were collected from the sector for various types of ships including single hull dry bulk ships, double hull dry bulk ships, double hull containerships, single hull tankers (no longer allowed on European inland waterways since January 2019), double hull tankers and dumb barges (with no propulsion of their own). In total 124 of the 157 certificates were used for the regression model and 33 certificates were used for validation. The dimensions of the 124 ships that were used to develop the model are plotted in Figure 3.

The dataset covers a broad range of ships operating on the Rhine, for which the maximum allowed length is 135 meters. Figure 2 shows clear patterns in the beam and length of the ships, which are a result of maximum allowed ship dimensions and length-dependent crew requirements for inland ships respectively. The logic behind the choice for certain main dimensions of inland ships is elaborately discussed by Hekkenberg (2013) and will not be addressed further in this paper.

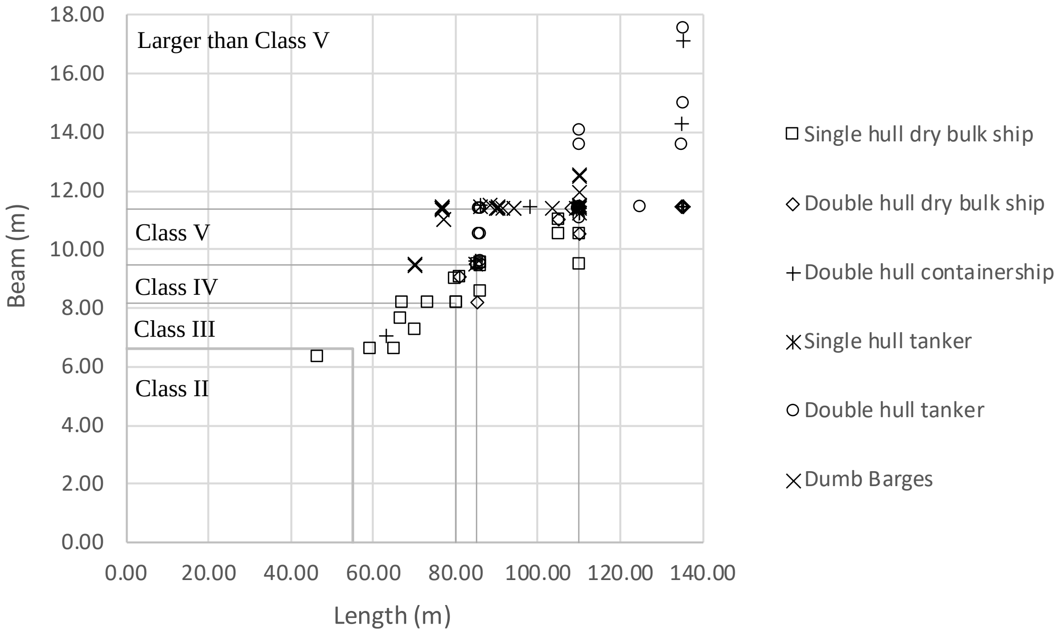


Figure 3. Selection of 124 ships included in regression model

The collected ship data was obtained by asking ship owners for their loading certificate and by analysing data of ships that were for sale or for which the loading certificate was available on the internet, which is common for dumb barges. Loading certificates were included on the basis of availability, but we aimed to cover a representative range of ships by requesting specific ship owners for their certificates in case of missing data. For dumb barges a selection was made from a large set of available loading certificates, in such a way that the full range of existing dimensions is reasonably covered, while avoiding the inclusion of a multiplicity of (near) identical dumb barges that would put too much weight on these points in the regression analysis. The dataset, therefore, provides reasonable coverage of ship dimensions in the West-European IWT fleet but is not usable to assess the 'average' ship size.

5. General model

Having gathered a substantial dataset of 157 loading certificates (of which 33 certificates are used for validation of the model outcome), the next step was to search for generic relations in the effect of low water on ship capacity. Ideally one would like to relate real deadweight tonnes to real water depths, for which the physical relations are the easiest to understand. However, plotting many deadweight-to-draft-relations for ships of different size and dimensions provides little insight other than that each ship is different. Therefore, to make the broader set of different ships comparable we analysed the relative effect of a reduced (or increased draft) on the loading capacity of the ships as an index of the capacity at a fixed reference draft. This capacity index was set at 100 for a draft of 2.50 m, because most ships are able to load at this draft or deeper (except for two Class II vessels with a maximum draft of 2.17 m and 2.44 m, for which we extrapolated the tonnage range to 2.50 m to define the reference capacity at an index of 100). We started to analyse the capacity reducing effects for ships of certain types and found, especially for containerships, that the relative change in ship capacity at changing water depths follows a similar trend regardless of the size of the ships. Figure 3 shows the capacity index for 17 container ships with dimensions varying from 63 x 7.0 m to 135 x 17.1 m.

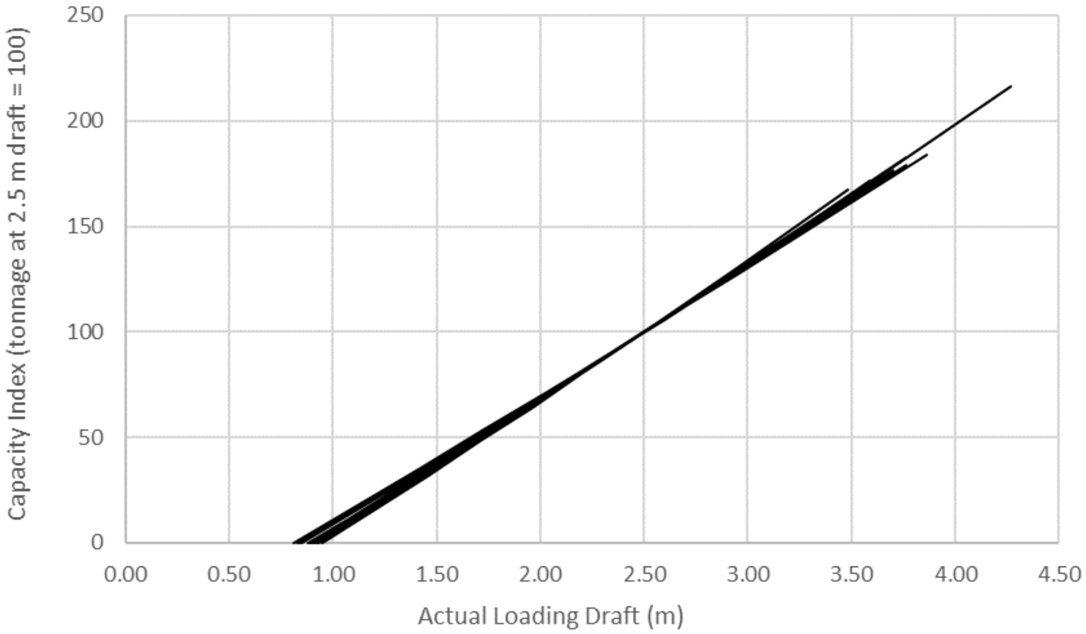


Figure 4. Capacity index at actual loading draft for 17 containerships in the dataset

For other ship types we found similar results but with larger spreads in the slope of the lines. We also found that some types, such as double hull tankers, were more affected by low water than others, like dumb barges. When analysing the data in more detail we found that the variance in the slope for ships of different type and size is almost entirely explained by the empty draft of the ships. This makes it possible to analyse the relative effect on ship capacity (as represented by the capacity index) for all ships combined regardless of their type and size. The result is a general model that can be used for all (West-European) inland cargo ships of Class II or higher (our dataset did not include any Class I ships and has not been validated for these small ships). Though the use of this model is less intuitive than the loading certificates of the individual ships, the model requires just to two basic parameters, being the empty- and actual loading draft (i.e. the draft for which the loading capacity is to be assessed).

In developing the model, we intended to give equal weight to each individual ship in the dataset. We, therefore, included 12 datapoints for each ship, starting with the empty draft and moving up to the full draft in 10 steps, but we also included the 100 indices at a draft of 2.5 meter to force the model to return an index close to 100 at a draft of 2.5 meter. For the 124 ships in the dataset this resulted in 1488 datapoints. The first regression model that we tried was a 2 parameter model with only the empty- and actual loading draft as input parameters. Please be aware that throughout this paper the empty draft always refers to the equal loaded empty draft as stated in the official loading certificate and not to the actual draft when taking trim effects into account. The results of this model are presented in Table 2 and plotted against the data in Figure 5. The data of the 33 ships that were kept aside for validation are also included in Figure 5.

Table 2. Results of the first regression model for defining the capacity index

Regression Outcome	Coefficients	St. Error	t Stat
Intercept	-4.0586904226E+01	0.768	-52.86
T_empty	-8.8346482721E+00	0.887	-9.96
T_actual	5.9321656186E+01	0.152	389.08

Regression Statistics	
Multiple R	0.995
R Square	0.990
Adjusted R Square	0.990
Standard Error	5.322
Observations	1488

The regression statistics suggest that the model performs quite well as al parameters seem to be significant and an adjusted R Square value of 0.990 was reported. However, the visual inspection of the model fit in Figure 5 shows that the results are not satisfactory over the entire range. Especially not at deeper drafts and for ships with a larger empty draft.

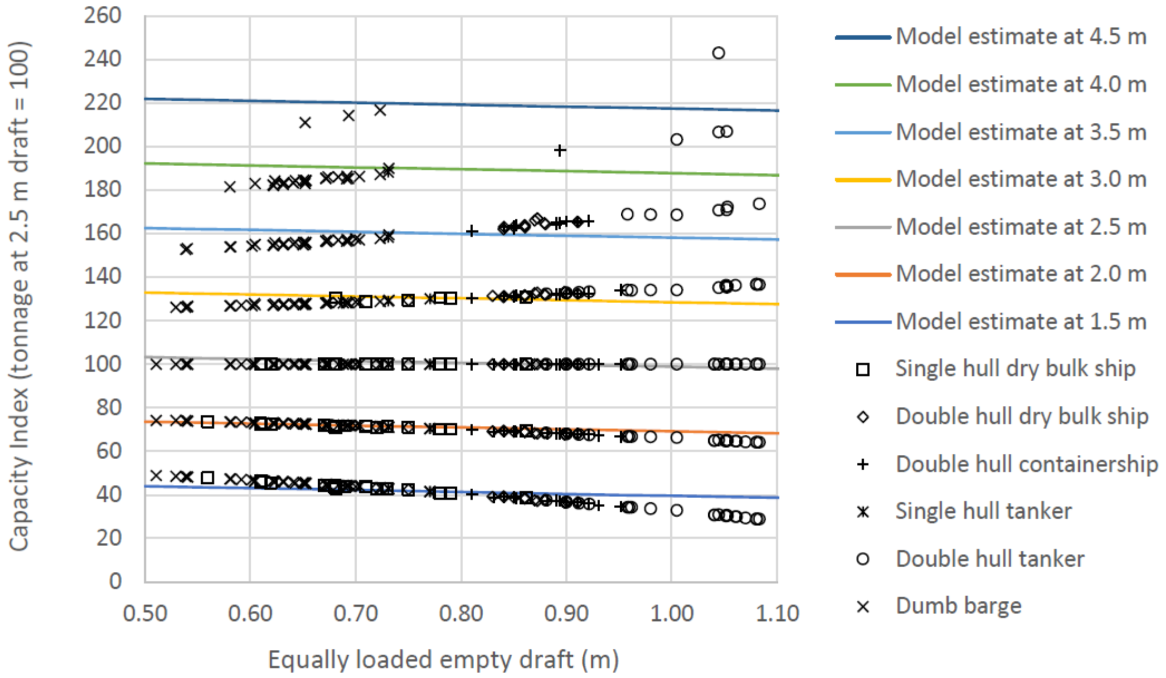


Figure 5. *Observed fit of the first regression model for capacity index*

As the objective of this paper is to present a general model that offers useful results even in case little is known about the details of the concerned ships, we searched for options to improve the fit without requiring additional input data (i.e. other than the empty draft and the actual loading draft). We tried a model that includes the squares of the empty and actual draft, and the product of empty and actual draft as additional input parameters. This second regression model has a much lower standard error of 0.67 (compared to 5.32 in the first model) and the t-statistics indicate that all five parameters are significant at the 99.99% confidence level. The model is presented in Table 3, together with the corresponding regression statistics that shows an Adjusted R Square of 1.000). The visual inspection and validation of the model, that will be discussed later, indicate that this second model has an exceptionally good fit and a fairly low variance. The fact that the regression model depends only on the empty draft and does not require specific input on type and size of ships (if the empty draft is known) can intuitively be understood as the block coefficient is quite similar for most inland ships.

Table 3. **Results of the second regression model for defining the capacity index**

Regression Outcome	Coefficients	St. Error	t Stat
Intercept	2.0323139721E+01	0.459	44.26
T_empty	-7.8577991460E+01	1.108	-70.94
T_empty^2	-7.0671612519E+00	0.681	-10.38
T_actual	2.7744056480E+01	0.113	245.60
T_actual^2	7.5588609922E-01	0.017	45.33
T_empty * T_actual	3.6591813315E+01	0.115	319.15

Regression Statistics	
Multiple R	1.000
R Square	1.000
Adjusted R Square	1.000
Standard Error	0.617
Observations	1488

When using the model, the coefficients are multiplied by the parameters indicated at the left side in Table 3, for which the intercept concerns the constant value in the regression equation. The use of the model is illustrated by Equation 2, in which CI stands for capacity index, Te for empty draft, Ta for actual draft, and all coefficients are rounded to 1 digit for illustration purposes.

$$\mathrm{CI} = 2.0\mathrm{E}+1 - 7.9\mathrm{E}+1 \cdot \mathrm{Te} - 7.1\mathrm{E}+0 \cdot \mathrm{Te2} + 2.8\mathrm{E}+1 \cdot \mathrm{Ta} + 7.6\mathrm{E}-1 \cdot \mathrm{Ta2} + 3.7\mathrm{E}+1 \cdot \mathrm{Te} \cdot \mathrm{Ta} \quad (2)$$

The model fit is visualised in Figure 6, and shows an excellent fit for all ship types including dumb barges, even at higher drafts, despite the fact that only a few deep drafted ships (and thus only a few datapoints) were included in the 124 ships of the applied dataset.

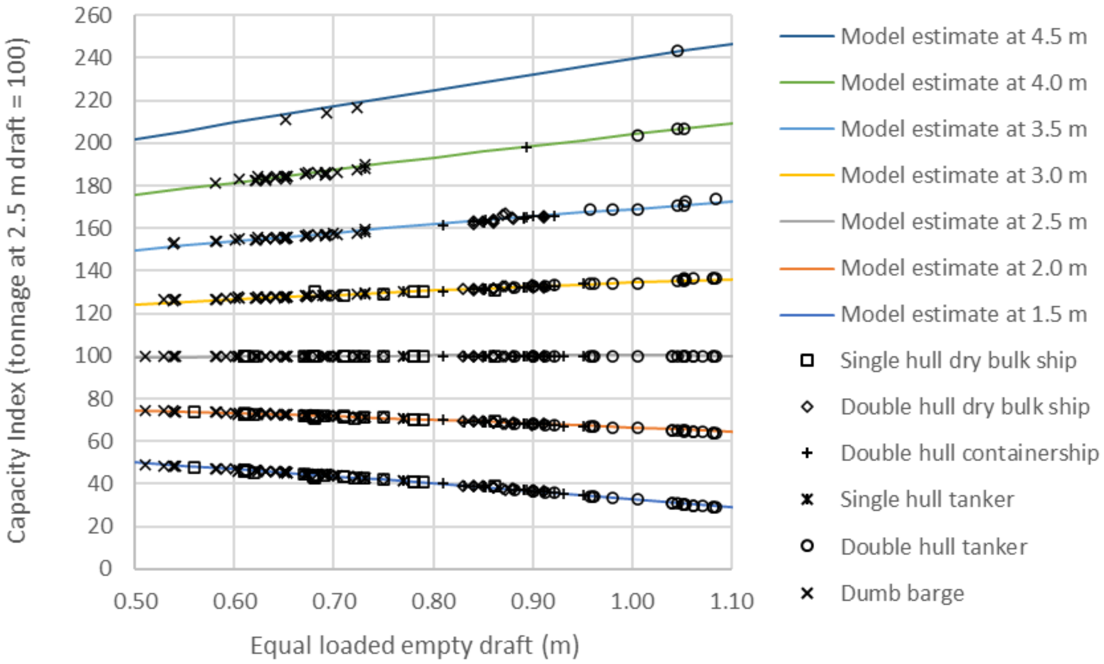


Figure 6. Observed fit of the second regression model for capacity index

The inclusion of the additional model variables was expected to improve the model fit as the individual loading curves fit well though a second degree polynomial function on the actual draft, but the outstanding performance of the second model is an unexpected empirical discovery for which we lack a further explanation.

To explain the use of the model, let's assume a situation in which a ship is normally able to load up to a draft of 3.0 meter (i.e. in case of sufficient water depth), but that due to low water it can only load at an actual draft of 2.0 meter. In this case the effect of the reduced draft on the ship's capacity is estimated by dividing the capacity index at 2.0 meter by the capacity index at 3.0 meter, which depending on the empty loading draft of the ship results in a remaining capacity of about 60% for a ship with an empty draft of 0.50 m and about 47% for a ship with an empty draft of 1.10 m (look up the corresponding index values from Figure 6 or apply the model presented in Table 3 to calculate them precisely). This corresponds to a reduction of about 40% to 53%. The capacity index model is thus a general tool for assessing the relative effects of reduced water depths on the deadweight of inland ships.

Presented in an alternative way, the model outcome provides an indication of the extent to which shipping operations, for ships with a different empty draft, are affected by low water restrictions. Figure 7 shows that ships with a high empty draft are more vulnerable to lower water depths than ships with a lower empty draft. Actual empty drafts included in the dataset ranged from 0.51 m for a dumb barge to 1.12 m for a double hull tanker.

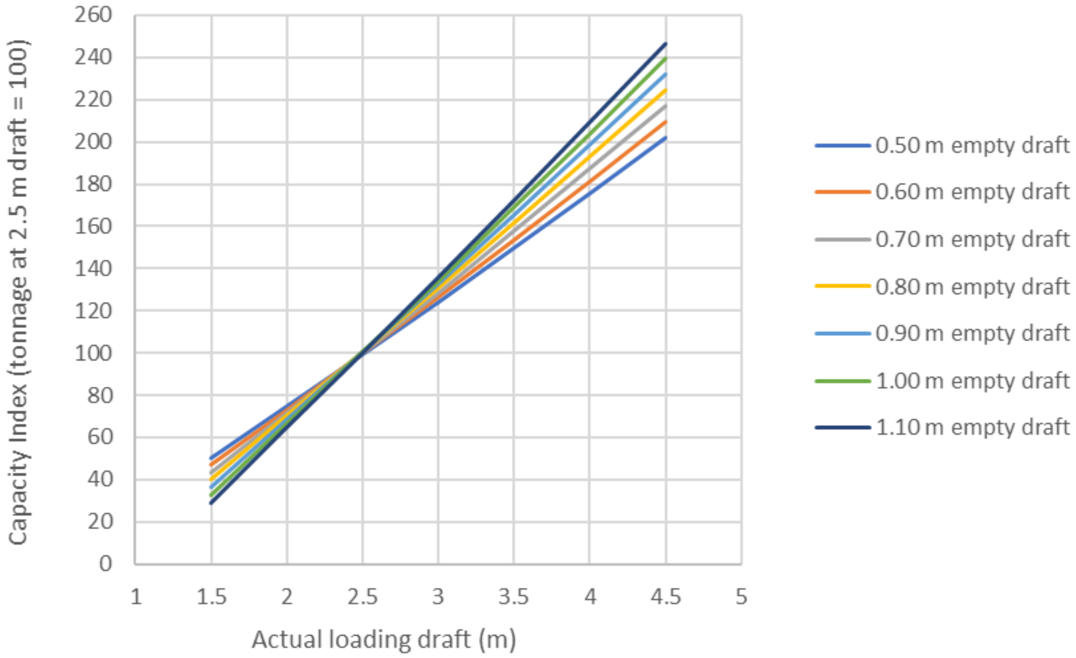


Figure 7. Capacity index for different empty and actual loaded drafts

6. Supporting models

The general model can be used to estimate the low water effects for individual ships, but for individual ships it is more accurate to look up the effects directly from the official loading certificates. This model is mainly developed to enable low water assessment models (such as BIVAS) to improve their estimates at the aggregated fleet level without requiring detailed information on the specific loading curves for the ship types and size classes included. The general model presented in Section 4 requires the empty draft to estimate the relative capacity effects and it requires the design draft and design capacity to estimate the effects in absolute terms. Since these input variables are not always known, this section presents three supporting models to estimate the empty draft, the design draft and the design capacity of inland ships, for which only the length, beam, ship type (tanker, bulk, container, and dumb barge) and hull type (single or double) serve as mandatory input. For the ship and hull type variables, dummy values are applied that can either be 1 or 0 depending on whether they are true or false. The dummy variable "Double Hull (Tanker)" is for instance 1 if the ship is a double hull tanker and 0 if it is not a tanker or not double hull ship.

6.1 Supporting model #1: Empty draft

For estimating the empty draft we considered a broad set of parameters that may be related to the size and relative weight of the ship and included: the beam; the length times the design draft divided by the beam; the square root of the length times the beam; and the product of length, beam and the design draft. In addition, three dummies were included for (1) double hull dry cargo vessels and containers; (2) double hull tankers; and (3) and dumb barges. The selection of these parameters has been made on the basis of the significance of the parameters and minimisation of the standard error. If the design draft is unknown it should be estimated first with supporting model #2. The empty draft model is indicated in Table 4.

The single hull dry bulk ship type was taken as basis for the model. This implies that no dummy was included for single hull dry bulk ships to avoid overspecification of the model. We have tested, but not included a dummy for single hull tankers, as the coefficient of this parameter was only -0.013 and the t-statistics had an insignificant value of -0.384.

Table 4. Supporting model to estimate the empty draft of inland ships

Regression Outcome	Coefficients	St. Error	t Stat
Intercept	7.5740820927E-02	0.104	0.73
Beam	1.1615080992E-01	0.017	6.68
(L * T_design)/B	1.6865973494E-02	0.003	6.19
(L * B)^0.5	-2.7490565381E-02	0.005	-5.24
L * B * T_design	-5.1501240744E-05	0.000	-4.06
Dummy DH Dry Bulk & DH Container	1.0257551153E-01	0.016	6.33
Dummy DH Tanker	2.4299435211E-01	0.018	13.39
Dummy Dumb Barge	-2.1354295627E-01	0.024	-8.97

Regression Statistics	
Multiple R	0.949
R Square	0.900
Adjusted R Square	0.894
Standard Error	0.051
Observations	124

* For dummy parameters, set value of variable to 1 if True; DH = double hull.

6.2 Supporting model #2: Design draft

For situations where the design draft is unknown, we propose a second supporting regression model. The development of this model is complicated by the fact that there is more variance in de design draft than in the empty draft. The design draft is, to a large extent, a choice of the owner of the ship, which implies that it depends on personal preferences. Ships with a lower design draft are lighter and able to carry more cargo in low water periods, whereas deeper drafted ships outperform low-design draft ships during normal and deep water conditions. Another complication is that especially containerships are often not registered up to the maximum load line for which they are designed in order to reduce port dues and inland waterway dues. Given that we want to develop a model that only requires a few basic input parameters such detailed aspects cannot be included in the model. We started looking at combinations of length, beam, length times beam, and some dummy variables as input data, for which length and beam turned out to be insignificant. Nevertheless, the resulting model still had large standard errors and was not satisfactory. We found that the model could be optimised by replacing the length times beam variable by the length to the power 'a' times the beam to the power 'b'. The parameters a and b were first optimised for each type of ship, by using a trend estimation function in combination with a solver in Excel. The result was a separate estimation model for each ship type with an optimised fit on length and beam. The obtained models were subsequently combined in a joint model for convenience. The result is presented in Table 5. The intercept is not included as each ship type has its own intercept and including an additional intercept would result in overspecification of the model.

Table 5. Supporting model for estimating the design draft of inland ships

Regression Outcome	Coefficients	St. Error	t Stat
Intercept	not included	N/A	N/A
Dummy Containers	1.7244153371E+00	0.377	4.57
Dummy Dry Bulk	2.2767179246E+00	0.090	25.29
Dummy Dumb Barge	1.3365379898E+00	0.379	3.53
Dummy Tanker	-5.9459308905E+00	0.919	-6.47
Dummy Containers * L^0.4 * B^0.6	6.2902305560E-02	0.013	4.82
Dummy Dry Bulk * L^0.7 * B^2.6	7.7398861528E-05	0.000	10.22
Dummy Dumb Barge * L^0.3 * B^1.8	9.0052384439E-03	0.001	7.23
Dummy Tanker * L^0.1 * B^0.3	2.8438560877E+00	0.277	10.28

Regression Statistics	
Multiple R	0.998
R Square	0.995
Adjusted R Square	0.986
Standard Error	0.256
Observations	124

* For dummy parameters, set value of variable to 1 if True.

Being able to define the design draft (that feeds into the model for the empty draft) and the empty draft (that feeds into the general model), the relative effect of reduced water depth on the capacity of inland ships can be defined for all concerned ship types.

6.3 Supporting model #3: Design capacity

To assess the capacity effects in tonnes rather than percentages of change, insight is required in the design capacity (or maximum tonnage) at design draft (or maximum draft). The third supporting model, therefore, defines the design capacity of the ship at design draft measured in deadweight tonnes (DWT). In developing the model, we first tried the relation between design draft and design capacity. This relation provided significant results but could be improved by taking the difference between the design draft and empty draft as explanatory variable rather than the design draft itself. This makes sense as the capacity can only build up over this draft range. However, when plotting the error term to the length times beam variable we still observed a remaining trend, which indicated that part of the explanatory power in the data was unused. A more accurate model was obtained by using both the design draft and the empty draft times the length and beam as separate input parameters (see Table 6).

Table 6. Supporting model for estimating the design capacity of inland ships

Regression Outcome	Coefficients	St. Error	t Stat
Intercept	-1.6687441313E+01	10.646	-1.57
L * B * T_design	9.7404521380E-01	0.005	210.56
L * B * T_empty	-1.1068568208E+00	0.020	-56.69

Regression Statistics	
Multiple R	0.999
R Square	0.999
Adjusted R Square	0.999
Standard Error	46.53
Observations	124

Note that the supporting model presented in Table 6 can also serve to provide an improved estimate of the empty draft when assessing ships for which the design draft and the DWT capacity are known. In that case the presented model:

$$DWT = a + b \cdot L \cdot B \cdot T_{design} + c \cdot L \cdot B \cdot T\_empty \tag{3}$$

can be rewritten as:

$$T_{empty} = \frac{DWT - a - b \cdot L \cdot B \cdot T\_design}{c \cdot L \cdot B} \tag{4}$$

With a, b, and c being the subsequent coefficients in the regression model of Table 6.

7. Model validation

The model is validated by plotting the estimated values against real values for both the model data (124 ships) and the validation data (33 ships) and by analysing the spread in the error terms for the validation data, for which the results are plotted in a histogram. This approach is conducted for the general model as well as for the three supporting models. For the general model 12 datapoints were included per ship, covering the full range from empty draft to design draft. For the supporting models only one datapoint was included as the outcome of these models is independent of the ship's actual draft.

Figure 8 shows the outcome of the general model, which has an excellent fit and shows only small errors for the model and validation data. The distribution of the errors in the validation data is indicated in the histogram and summarised by the mean absolute error (MAE) and the root mean square error (RMSE) for the validation data.

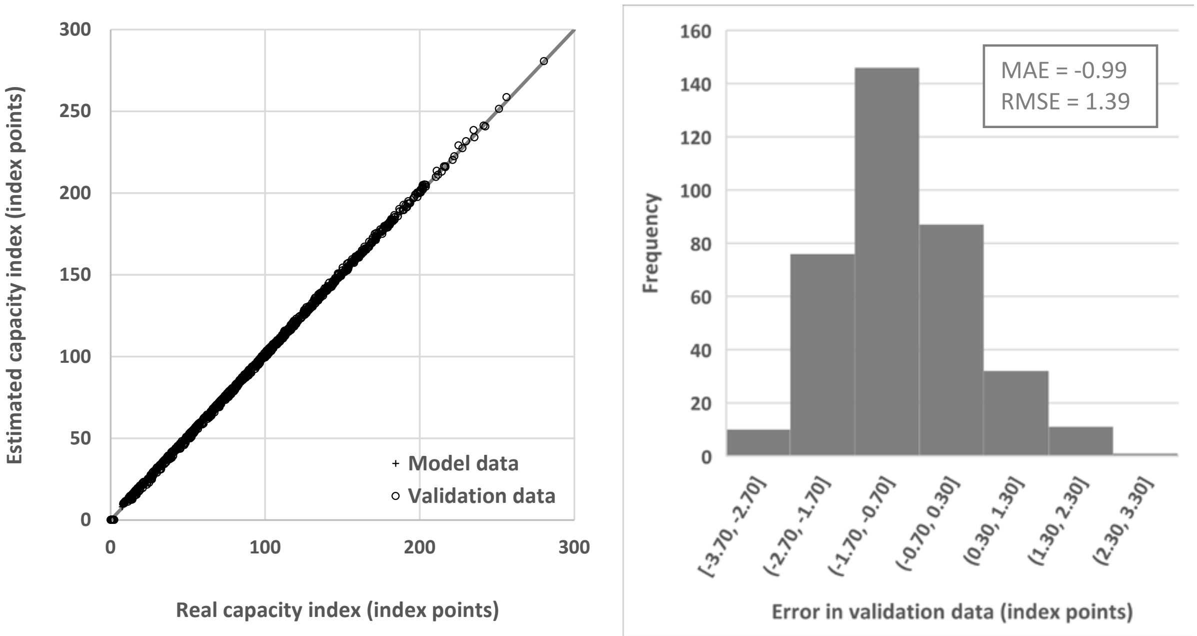


Figure 8. General model validation and histogram of error terms

Figure 9 shows the accuracy of the first supporting model for defining the empty draft (using the real design draft as input variable rather than the estimated value from supporting model 2). Although all parameters are significant there remains noticeable variation that cannot be explained by the type and size of the vessel alone, as indicated in the histogram with errors ranging between -9 and +11 cm for the validation data. This variation reflects the preferences of the ship owners, that can choose between building a light but less sturdy ship or a more sturdy one with a heavier steel construction. Both Hofman (2006) and Hekkenberg (2013) noted that there are significant discrepancies between the actual weight of the ship's structure and the (lower) weight limit that could be achieved on the basis of classification society rules. This is variance we need to live with and cannot reduce without requiring more detail.

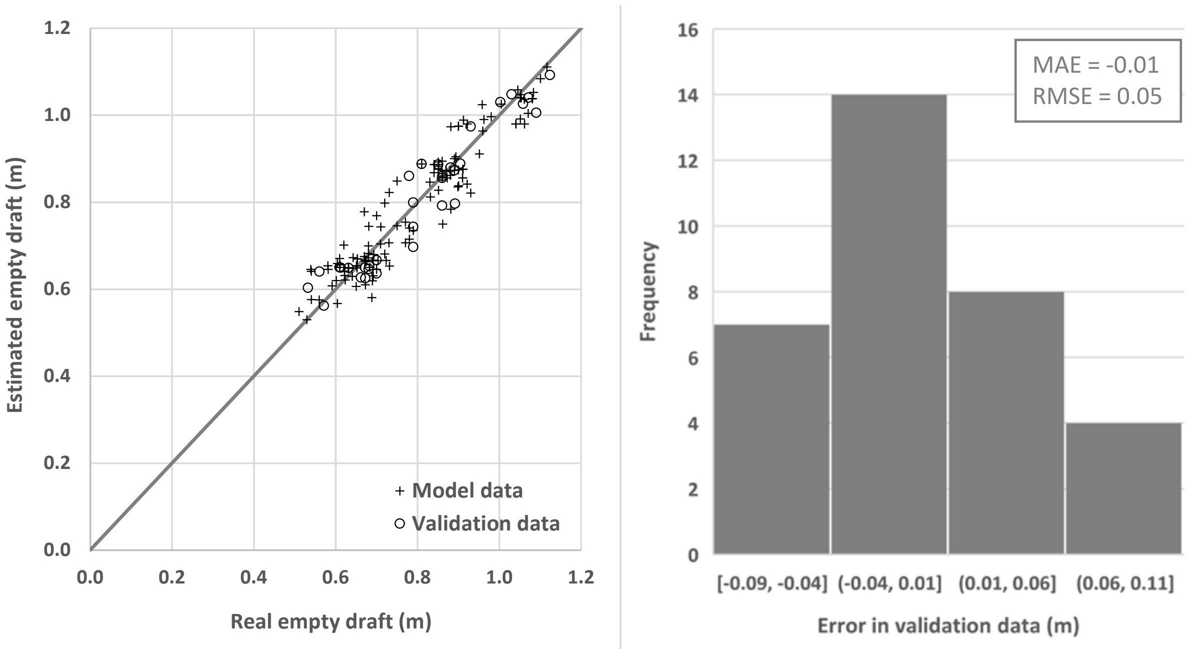


Figure 9. Empty draft model validation and histogram of error terms

Figure 10 shows the variance for the design draft, which is larger than for the empty draft. The spread in the validation data for the empty and the design draft seems quite similar to the spread in the model data, which is in line with our expectations as no specific criteria was applied for selecting the model and validation data other than that we selected the model data to have a broad coverage of ship sizes.

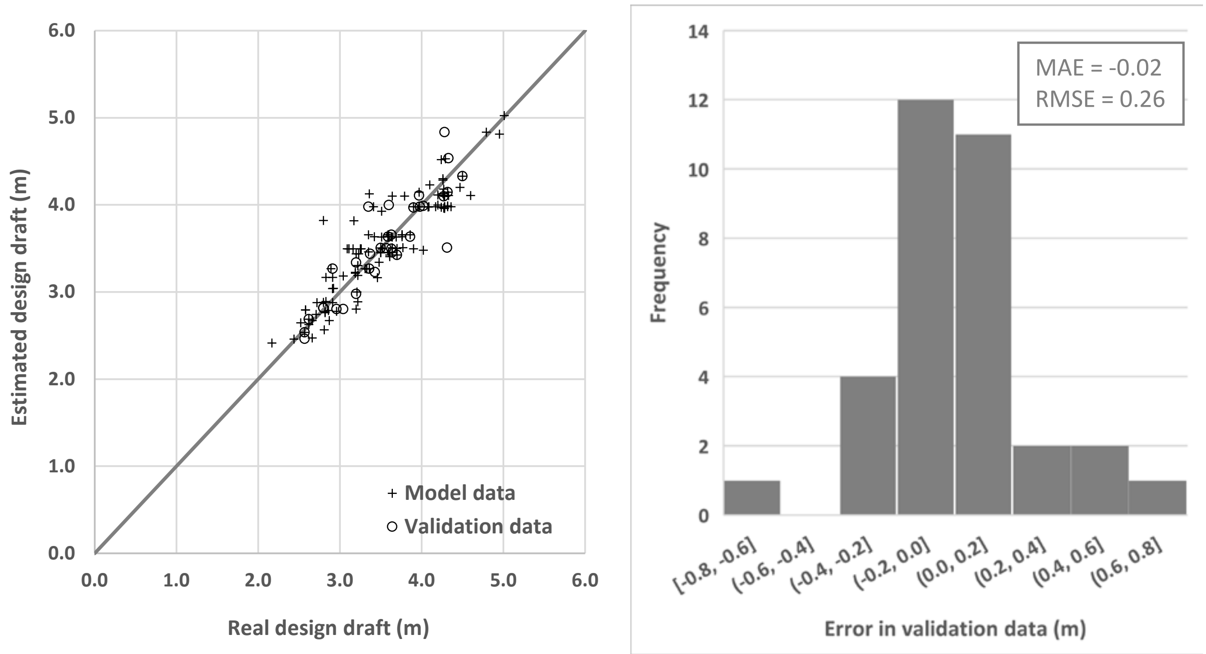


Figure 10. Design draft model validation and histogram of error terms

Figure 11 shows the model fit and variance for the design capacity when using both the real empty draft and the design draft as input values. This model has a good fit and little variance.

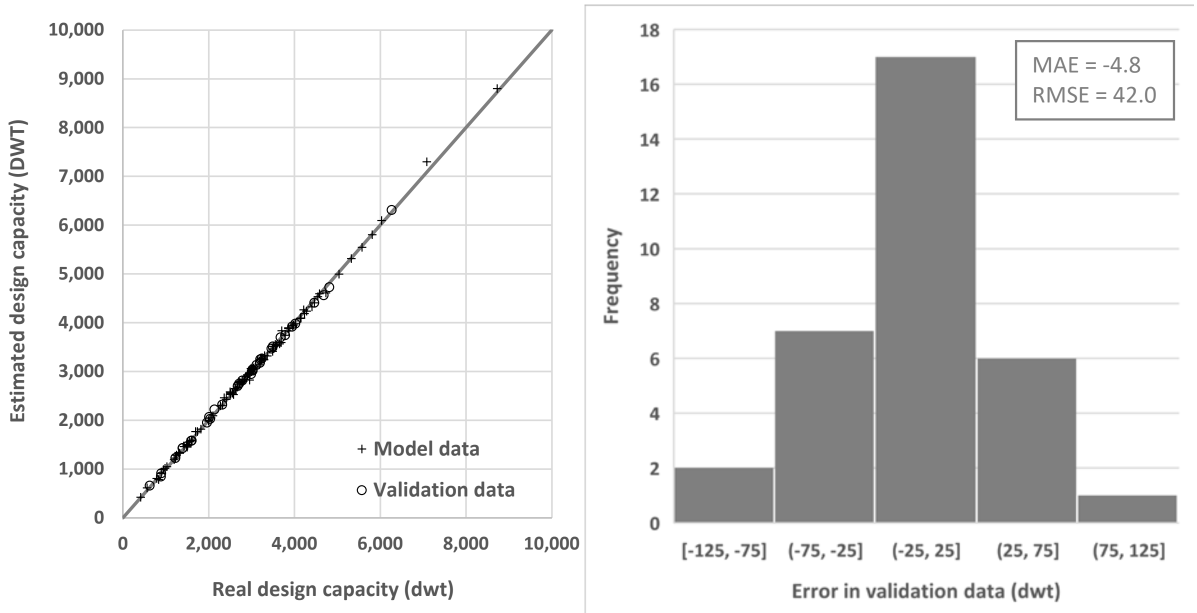


Figure 11. Design capacity model validation and histogram of error terms

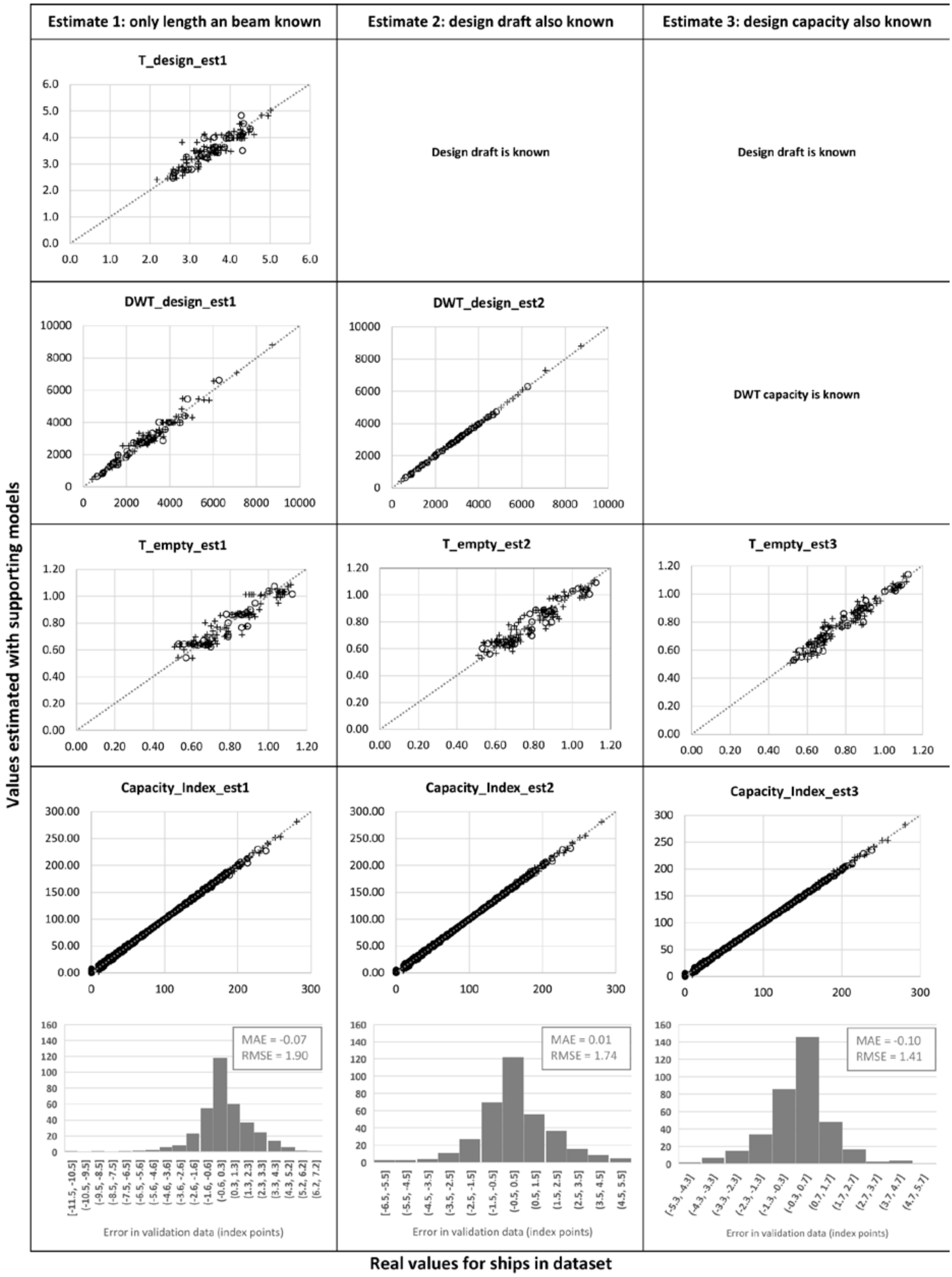


Figure 12. Combined model validation and histogram of error terms

In Figure 8 to 11 we validated the quality of the individual models assuming their input data is known. Thus far, we have not looked into the combined errors when using supporting models to estimate the design draft, empty draft, and the design capacity. This analysis is indicated in Figure

12, that shows the real versus the estimated output values for both the model data (indicated with +) and the validation data (indicated with o), as well as the error term in the capacity index. The figure shows that the model fit improves and the spread in the error terms reduces when more information is available. Note that the situation in which the empty draft is precisely known is already presented in Figure 8 and not repeated in Figure 12.

There is remarkably little variance in the relative capacity index (i.e. the calculated capacity index) for all concerned estimates in Figure 8 and 12. This is surprising because there is substantial variance in the empty and design draft estimates that serve as input to the general model. This implies that only small errors are made when the capacity index is calculated on the basis of estimated values for the design draft, design capacity and empty draft, but the estimates do improve when the real values are known.

Note that errors in absolute capacity are larger than the errors in relative capacity when the absolute capacity is based on estimates of the design draft and the design capacity. The explanation for this can be found in the fact that if the empty or design draft is estimated with a certain error, the error in capacity works in the same direction for all drafts including the baseline draft, for which the error in the quotient of two drafts (i.e. the relative error) is reduced. When assessing errors in absolute capacities, an error made in estimating the empty or design draft propagates over the entire draft range of the vessel.

8. Model application

To illustrate the use of the model, let's consider the situation in 2018 on the Dutch part of the Rhine (i.e. the river Waal) where the least measured water depth was 1.60 m while normally 2.80 m is to be guaranteed. What is the effect of these extreme low water conditions on the carrying capacity of a 110 x 11.45 m inland container ship sailing to Germany?

First, from Table 1 we find that for container ships sailing on a stone riverbed an under keel clearance of about 20 cm is suggested. This implies that the ship's allowable draft is reduced from 2.60 m to 1.40 m. If the design and empty draft are not known, one can first estimate the design draft from the model presented in Table 5, which is 3.50 m, and then estimate the empty draft with the model presented in Table 4, which is 0.87 m. From applying the model presented in Table 3 one finds a capacity index of 106.6 at 2.60 m and of 31.4 at 1.40 m, resulting in a remaining capacity fraction of 29% (i.e. 31.4/106.6). This implies a reduction in deadweight by 70.4% compared to the guaranteed water depth of 2.80 m. When considering a uncertainty of ± 10 cm on the applied under keel clearance (as suggested in Section 2) the corresponding capacity reduction is 66.7% at the lowest under keel clearance and 74.7% at the highest under keel clearance.

The absolute effect on loading capacity (in tonnes rather than as an index) is calculated by the following steps. One first defines the design capacity with the model presented in Table 6, which is 3066 tonnes for the concerned ship. The next step is to define the relative capacity index at 3.50 meter, which is 164.8. This implies that the baseline capacity is 1865 tonnes (i.e. 3066/164.8). The absolute capacities at 1.40 and 2.60 meter are respectively 584 tonnes (i.e. 1865 * 31.4/100) and 1984 tonnes (i.e. 1865 * 106.6/100). The difference in absolute loading capacity between 2.60 meter and 1.40 meter is thus 1400 tonnes (i.e. 1984 – 584). Finally, one can also calculate that the loading capacity at 1.40 meter draft is just 19% of the deep water capacity (i.e. 584/3066).

If one desires to estimate the effects on payload, rather than on deadweight, one may assume that during normal deep water conditions the non-payload part of deadweight (i.e. the consumables) is in the order of 6% of the design deadweight, whereas it is reduced to just 4% of the design deadweight under conditions of extreme low water. This would imply a payload at design draft of 3.5 meter of about 2882 tonnes (i.e. 3066 – 6% * 3066) and a low water payload of just 461 tonnes at

1.40 meter draft (i.e. 584 – 4% * 3066). For dumb barges consumables are assumed to be negligible except when they are self-propelled (e.g. by bow thruster) or equipped with a deckhouse to support a crew.

To illustrate the potential insights that can be obtained from the model, Table 7 shows for 18 ships of various type and size the capacity at design draft and the capacity at the lowest draft for which they can just continue operations (as indicated with an *).

Table 7. Effect of low water on deadweight and payload capacity of inland ships

Operational conditions		Deep water design draft			Minimum operational draft*		
CEMT Class	Ship dimensions	Draft [m]	DWT [tonnes]	Payload [tonnes]	Draft* [m]	DWT* [tonnes]	Payload* [tonnes]
			Tankers (double hull)				
Class IV	85 x 9.50 m	2.77	1316	1237	1.30	247	194
Class V	110 x 11.40 m	3.50	2849	2679	1.40	432	318
Class VI+	135 x 17.50 m	5.02	8759	8233	1.50	955	604
			Dry bulk ships (single hull)				
Class II	55 x 6.00 m	2.41	537	505	1.20	176	155
Class III	80 x 8.20 m	2.67	1202	1130	1.20	309	261
Class IV	85 x 9.50 m	2.88	1612	1516	1.30	422	358
Class V	110 x 11.40 m	3.44	3125	2937	1.40	710	585
			Dry bulk ships (double hull)				
Class IV	85 x 9.50 m	2.88	1521	1429	1.30	340	279
Class V	110 x 11.40 m	3.44	2982	2803	1.40	588	469
Class VI	135 x 11.40 m	3.62	3944	3707	1.50	874	716
			Containerships (double hull)				
Class III	63 x 7.00 m	2.78	802	754	1.20	162	130
Class IV	85 x 9.50 m	3.16	1713	1610	1.30	318	250
Class V	110 x 11.45 m	3.50	3066	2882	1.40	584	461
Class VI	135 x 14.25 m	3.93	5499	5169	1.50	1083	863
Class VI+	135 x 17.50 m	4.22	7307	6878	1.50	1238	945
			Dumb barges				
Class IV	70 x 9.50 m	3.19	1649	1649	1.30	472	472
Class V	77 x 11.40 m	3.98	2763	2763	1.40	604	604
Class V	90 x 11.40 m	4.11	3370	3370	1.40	716	716

Note: For Class III container ships smaller ship dimensions have been used in line with what is common in practice. The same hold for Class VI ships that are formally defined at 135 x 15 m but usually about 14.25 meter wide. Inland ships are indicated as Class VI+ when the width exceeds the 15 m used in the CEMT 1992 classification.

The following steps have been applied to calculate the table:

- Define the length, beam and type of ship for which the design capacity, the effect on reduced low water capacity, and the payload is to be estimated;
- Define the minimum draft at which the ships can still continue operations by applying the default values in Table 1;
- Define the design draft by applying the regression model presented in Table 5;
- Define the empty draft by applying the regression model presented in Table 4;
- Define the corresponding design capacity in deadweight tonnes for the design draft by applying the regression model presented in Table 6;
- Calculate the capacity index for both the design draft and the minimum operational draft by applying the regression model presented in Table 3, wherein the actual draft is set at the values of the design and minimum operational draft;

- Define the deadweight at minimum operational draft by multiplying the design capacity by the quotient of the capacity index at low water and at design draft;
- Define the payload at design draft by subtracting an assumed percentage of the deadweight for consumables, for which a default value of 6% of the design capacity is assumed, similar to the average of the range discussed in Section 3.
- Define the payload at low water conditions by subtracting a reduced percentage for consumables from the deadweight assuming that ship owners will try to minimize consumables in order to improve payload, for which a reduced value of 4% of the design capacity at design draft is assumed.
- For dumb barges that are usually transported with pusher units down to a minimum required pusher draft of 1.70 meter, it is assumed that they are carried by other ships (i.e. taken alongside) in times of extreme low water conditions. Dumb barges have little or no consumables, so the payload is assumed equal to the deadweight.

9. Conclusions and further discussion

Literature on inland waterway transport lacks an accurate model to define the effect of reduced water depths on the capacity of inland ships during extreme low water conditions, while such a model is increasingly needed to assess the cost effectiveness of options to maintain sufficient water depth in the light of climate change.

This paper presents a general empirical model that can be used to estimate the effect of changing water depths on the capacity of inland ships as well as three supporting models for estimating the relevant input parameters in case these are not known. The model is based on operational observations made during the extreme low water period of 2018 and on real data on the draft-to-tonnage relation obtained from the loading certificates of 124 inland ships and dumb barges. It incorporates insights that are available at the operational level of the individual ships and presents it in a way that is useful to scientists and policy advisors.

Loading certificates of another 33 ships and dumb barges were used to validate the model. It is concluded that there is little variance in the outcome of the general model, despite larger variance in the supporting models that feed into the general model.

The model is simple in the sense that it only requires the length, beam and hull type of the ships to be known, but estimates can be improved with additional information on design draft, design capacity and empty draft. The presented model structure can feed directly into policy-supporting models for analysing the effects of climate change and river adjustments on inland shipping to improve the assessment of low water effects on the loading capacity of inland ships. It may, for example, be used to replace the modelling approach presently applied in BIVAS, that is considered less accurate at more extreme low water levels.

Despite substantial improvement in modelling of inland ship capacity at constrained water conditions, there remain areas for which further study is recommended. First, the assumptions on minimum required water depth as presented in Table 1 may be improved by modelling the actual draft taking into account the trim of the vessel at critical low water conditions. Second, the assumptions on the applied minimum under keel clearance could benefit from a broader consultation study and actual measurements, to verify the assumptions made in this paper. Third, additional data on smaller ships would allow the model to be validated and extended for the smallest Class I category of inland ships. Fourth, the model application is developed using data from ships in the West-European fleet. This implies that the model is not readily applicable for assessing the impact of low water in other parts of the world. In fact, the model needs to be validated and parameters may need to be redefined with data from loading certificates of inland ships operating in other areas. Substantial improvements are further expected from a more in-depth study of the relation between deadweight and payload, especially at critical low water conditions. Finally, in order to assess the effect of lower available water depth on the overall logistical capacity of all the ships in the fleet, insight is required in the extent to which ships are able to adapt their speed and increase operational hours during severe low water periods.

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