Quantifying water transport performance in estuaries

An agent-based method to facilitate system modification trade-offs in multi-stakeholder settings

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Dissertation

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by

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Keywords: Port congestion, Tidal downtime, Estuary, Waiting times, Freshwater availability, Saltwater intrusion, Trade-off curve

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The cover is inspired by transit maps, a personal passion of mine, and schematises the main waterways of the key section of the Rhine-Meuse Delta. The network consists of nodes, interchange stations representing navigation lock complexes, and edges. The width of the edges represents the importance of the waterway: widest edges represent seagoing traffic routes, second widest edges represent important inland waterway routes, and the narrowest edges represent secondary inland barge routes. The edges are furthermore coloured by a salinity-themed colour map: yellow colours represent saline waters, while light blue colours represent fresh waters, green to dark blue transitional colours represent brackish waters. The extent of the saltwater intrusion reflects the actual situation during a severe, prolonged drought combined with a heavy north-western storm, and the absence of water management measures. In summary, the map combines hydrodynamics and ports and waterway logistics—the central theme of this dissertation—focused on the main case study presented here.

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Summary

This dissertation is triggered by the prevalent observation of conflicting stakeholder interests in highly urbanised deltas. These are coastal areas containing estuaries — i.e., water bodies where river water meets and mixes with seawater —– which can form open or closed systems, and which can be natural or (highly) modified (e.g., trained, dredged or closed-off channels and canals). In these deltas, many stakeholders, including local communities, agriculture, shipping, and ecology, rely on estuarine services such as water safety, freshwater availability, deep and calm waters, and natural dynamics. Due to climate change and socioeconomic developments, many of these estuaries have become increasingly pressured, meaning that during extreme conditions, such as droughts, the variety of stakeholder interests can no longer be simultaneously satisfied. Consequently, system modifications to improve one stakeholder's interest may come at the expense of other stakeholders' interests, requiring complex trade-off decisions.

Here, waterborne transport is a key player. To facilitate the movement of goods and people, water transport entrepreneurs employ ever-larger vessels that call at ports ever more frequently. To accommodate this trend, waterways have been deepened and new lock complexes have been constructed. While such system modifications have brought beneficial effects to regional and (inter)national economies, they have also exacerbated saltwater intrusion, which negatively impacts freshwater availability during droughts. A framework to quantify a fair trade-off between the interests of waterborne transport and other estuarine user functions is currently absent. Instead, policy and decision-makers rely on qualitative analyses based on oversimplified models, hindering rational policy and decision-making. This problem particularly holds for the impact of physical system changes on waterborne transport performance, which are often not quantified. Consequently, interventions aimed at improving waterborne transport often neglect the potential negative impacts on other stakeholders, leading to suboptimal and non-integrated solutions that may be ineffective in the long run.

The objective of this dissertation is therefore to assemble a methodological framework that can rationally quantify the trade-offs between impacted stakeholder interests for interventions in systems where waterborne transport plays a significant role. To achieve this, a two-step approach is followed. First, a method is developed to quantify the impact of system modifications in estuaries on waterborne transport performance. Second, this quantification method is included in a framework that can evaluate multi-stakeholder interests for an intervention in the estuary. This framework results in a trade-off curve between the impacts on the stakeholders' key performance indicators.

As a result of the first step, this dissertation found that vessel waiting times are the key performance indicator for quantifying the impact of system modifications on water transport. These waiting times are primarily caused by the cascading effects of downtime and congestion, which are currently not quantified by any existing method. To include these effects, this dissertation identified the open-source simulation library OpenTNSim to be the most suitable for further development. Additional modules were developed and added to this library to resolve the aforementioned 'cascading effects of downtime and congestion' for both open and closed estuarine systems. The proposed quantification method was validated by its implementation as a nautical traffic model in a real-world case study of seagoing vessels calling at a liquid bulk terminal in the Port of Rotterdam. In this case, the nautical traffic model was considered valid when a sufficient part of observed waiting times could be reproduced and explained. One year of AIS data was analysed to obtain a representative fleet in the model with realistic origins, destinations, speeds, turning times, and laytimes at the terminal and anchorage areas. In addition, geospatial data and one year of hydrodynamic data were used to derive model input. Together with the actual maintained bed levels, port layouts, and tidal accessibility policies, the model resolves tidal downtime and infrastructure congestion. Analysis of the model results reveals that the nautical traffic model was able to unravel 73.4% of the observed

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non-excessive vessel waiting times. Moreover, the unresolved excessive waiting times are believed to be caused by other processes that are not related to the system's state. Hence, the implemented method is considered valid to quantify waterborne transport performance as a function of the physical system.

In the second step, the now-validated quantification method for waterborne transport performance was included in a developed framework to evaluate trade-offs between the stakeholders' interests. The framework entails a train of models that link state indicators of the physical system to performance metrics for stakeholder interests. The model results are used to quantify the trade-off between port performance and freshwater availability as a function of bed-level variations in the open system of the Nieuwe Waterweg (NWW) in the Rhine-Meuse Delta. The resulting impact curves are insightful; they reveal how waterborne transport performance and freshwater availability compete as the bed level of the NWW changes. Freshwater availability improves when the bed level is raised, albeit at the expense of water transport performance, while water transport performance improves when the NWW bed level is lowered, albeit at the expense of freshwater availability elsewhere in the estuary. By adding valuation functions to each of the performance curves, stakeholders can express how important they find certain levels of performance loss. Ultimately, the framework leads to an optimal depth, although this decision remains a political process.

In conclusion, this dissertation enables a more rational trade-off between stakeholder interests in estuaries where water transport plays an important role. The underlying agent-based nautical traffic modelling method, implemented in the OpenTNSim library, and trade-off framework can be further expanded and applied. For this, further validation of the modules is recommended, particularly for closed systems, as they were only validated for open estuaries, with a specific focus on tidal windows and salt intrusion effects. Furthermore, to extend the applicability of the proposed quantification method for water transport performance, this dissertation recommends considering the incorporation of additional physical factors that affect downtime and additional sources that contribute to congestion. This may require the incorporation of additional datasets and the involvement of additional computing power. Moreover, to extend the applicability of the trade-off framework, it is advised to incorporate additional stakeholder interests and to involve stakeholders in constructing realistic valuation functions. With these additions, the proposed approach becomes more widely applicable, opening the door to its application to other estuaries around the world.

Samenvatting

Dit proefschrift is ingegeven door de veelvoorkomende observatie van conflicterende belangen van belanghebbenden in sterk verstedelijkte delta's. Dit zijn kustgebieden met estuaria — d.w.z. watersystemen waarin rivierwater samenkomt en mengt met zeewater — die open of gesloten systemen kunnen vormen, en die natuurlijk of (sterk) gemodificeerd kunnen zijn (bijv. getrainde, (uit)gebaggerde of afgesloten geulen en kanalen). In deze systemen bevinden zich veel belanghebbenden, zoals lokale gemeenschappen, landbouw, ecologie en scheepvaart, die afhankelijk zijn van estuariene diensten zoals waterveiligheid, zoetwaterbeschikbaarheid, diep en kalm water en natuurlijke dynamiek. Veel van deze estuaria zijn echter onder druk komen te staan door klimaatverandering en sociaaleconomische ontwikkelingen, wat betekent dat tijdens extreme omstandigheden, zoals droogte, de verschillende stakeholderbelangen niet langer tegelijkertijd tegemoet kunnen worden gekomen. Deze situatie kan ervoor zorgen dat systeeminterventies om het belang van één stakeholder te verbeteren, ten koste gaan van de belangen van andere stakeholders, wat dus complexe afwegingen vereist.

Hierbij speelt transport over water een sleutelrol: om het vervoer van goederen en mensen te vergemakkelijken, zetten transportondernemers steeds grotere schepen in, die dan ook steeds vaker aanlopen in havens. Om deze trend te faciliteren, zijn waterwegen verdiept en zijn nieuwe sluizencomplexen aangelegd. Hoewel dergelijke systeeminterventies gunstige gevolgen hebben gehad op de regionale en (inter)nationale economieën, hebben ze ook de zoutindringing verergerd, wat negatieve gevolgen heeft voor de zoetwaterbeschikbaarheid tijdens droogte. Echter ontbreekt er momenteel een raamwerk voor het kwantificeren van een eerlijke afweging tussen het belang van transport over water en andere estuariene gebruiksfuncties. In plaats daarvan vertrouwen beleidsmakers en besluitvormers op kwalitatieve analyses die gebaseerd zijn op sterk vereenvoudigde modellen, wat rationele beleids- en besluitvorming belemmert. Dit probleem geldt met name voor de impact van fysieke systeemveranderingen op de prestaties van het transport over water, die vaak niet gekwantificeerd (kunnen) worden. Daardoor zouden interventies gericht op het verbeteren van het transport over water negatieve impact kunnen veroorzaken op andere stakeholders, wat leidt tot suboptimale en niet-geïntegreerde oplossingen die op de lange termijn ineffectief kunnen zijn.

Het doel van dit proefschrift is daarom het samenstellen van een methodologisch raamwerk voor het rationeel kwantificeren van de afwegingen tussen de belangen van getroffen stakeholders voor interventies in systemen waar transport over water een belangrijke rol speelt. Om dit te bereiken wordt een tweestaps benadering gevolgd. Ten eerste wordt een methode ontwikkeld om de impact van fysieke systeemveranderingen in estuaria op de prestaties van het transport over water te kwantificeren. Ten tweede wordt deze kwantificatiemethode opgenomen in het raamwerk dat de belangen van meerdere stakeholders voor een interventie in het estuarium kan evalueren. Dit raamwerk resulteert in een afweegcurve tussen de impact op de belangrijkste prestatie-indicatoren van de stakeholders.

Als resultaat van de eerste stap werd bevonden dat wachttijden van schepen de belangrijkste prestatie-indicator is bij het kwantificeren van de impact van veranderingen in het fysieke systeem op de scheepvaart. Deze wachttijden worden vooral veroorzaakt door cascade-effecten van downtime en congestie, welke momenteel door geen enkele berekeningsmethode volledig kunnen worden ingeschat. Om deze effecten toe te voegen, werd de open-source simulatiebibliotheek OpenTNSim van de beschikbare methoden als de meest geschikte voor verdere ontwikkeling gevonden. In deze bibliotheek zijn aanvullende modules ontwikkeld en toegevoegd om de eerder genoemde 'cascade-effecten van downtime en congestie' te kunnen modelleren in zowel open als gesloten estuarine systemen. Deze zijn gevalideerd door de implementatie van de methode als nautisch verkeersmodel in een casusstudie over het gedrag van zeeschepen die aanlopen bij een natte bulk terminal in de haven van Rotterdam. Hiervoor werd het model als valide beschouwd wanneer een voldoende deel van de waargenomen wachttijden kan worden gereproduceerd en verklaard. Eén jaar aan

AIS-gegevens werd geanalyseerd om in het model een representatieve vloot te verkrijgen met realistische herkomst, bestemming, snelheid, draaitijden en ligtijden op de terminal en ankerplaatsen. Daarnaast werden geo-ruimtelijke gegevens en één jaar aan hydrodynamische gegevens gebruikt om modelinvoer af te leiden. Samen met de werkelijk onderhouden bodemniveaus, havenlayouts en toegangsrichtlijnen voor getij addresseert het model de getijdenbeperkingen als downtime en infrastructuurcongestie op. De analyse van de modelresultaten wees uit dat het nautisch verkeersmodel 73,4% van de waargenomen niet-excessieve scheepswachttijden kon achterhalen. Bovendien wordt er aangenomen dat de onopgeloste excessieve wachttijden worden veroorzaakt door andere processen die geen verband houden met de systeemtoestand. Daarom wordt de geïmplementeerde methode als valide beschouwd om de prestaties van het transport over water te kwantificeren als functie van het fysieke systeem.

In de tweede stap werd de nu gevalideerde kwantificatiemethode voor de prestaties van het transport over water opgenomen in een ontwikkeld raamwerk voor het evalueren van afwegingen tussen de belangen van de stakeholders. Het raamwerk omvat een reeks modellen die toestandsindicatoren van het fysieke systeem koppelen aan prestatiemetrieken van de stakeholders. Het raamwerk werd gebruikt om de afweging tussen havenprestatie en zoetwaterbeschikbaarheid te kwantificeren als functie van variaties in bodemniveau in het open systeem van de Nieuwe Waterweg (NWW) in de Rijn-Maasdelta. De resulterende impactcurves zijn verhelderend; samen laten ze zien hoe de prestaties van het transport over water en de zoetwaterbeschikbaarheid concurreren naarmate het bodemniveau van de NWW verandert. De zoetwaterbeschikbaarheid verbetert wanneer het bodemniveau wordt verhoogd, zij het ten koste van de prestaties van het transport over water, terwijl de prestaties van het transport over water verbeteren wanneer het bodemniveau van de NWW wordt verlaagd, zij het ten koste van de zoetwaterbeschikbaarheid elders in het estuarium. Door aan elke prestatiecurve waarderingsfuncties toe te voegen, kunnen stakeholders aangeven hoe belangrijk ze bepaalde niveaus van prestatieverlies vinden. Het raamwerk resulteerd uiteindelijk in een optimale diepte, al blijft zo'n besluit onderhevig aan de politiek.

Concluderend maakt dit proefschrift een meer rationele afweging mogelijk tussen de belangen van stakeholders in estuaria waar transport over water een belangrijke rol speelt. De onderliggende agent-based nautische verkeersmodelleringsmethode, geïmplementeerd in de OpenTNSim-bibliotheek, en het afweegraamwerk kunnen verder worden uitgebreid en toegepast. Hiervoor wordt aanbevolen om de modules verder te valideren, met name voor gesloten systemen, aangezien deze alleen zijn gevalideerd voor open estuaria, met een specifieke focus op getijdenvensters en zoutindringingseffecten. Bovendien, om de toepasbaarheid van de voorgestelde kwantificatiemethode voor transport over waterprestaties uit te breiden, beveelt dit proefschrift aan om aanvullende fysieke factoren die invloed hebben op downtime, evenals extra bronnen die bijdragen aan congestie, in het model te integreren. Dit kan de integratie van aanvullende datasets en extra rekenkracht vereisen. Om de toepasbaarheid van het afweegraamwerk verder uit te breiden, wordt geadviseerd om aanvullende stakeholderbelangen op te nemen en stakeholders te betrekken bij het construeren van realistische waarderingsfuncties. Met deze toevoegingen wordt de voorgestelde aanpak breder toepasbaar, wat de deur opent voor toepassing in andere estuaria wereldwijd.

Preface

With the world's population projected to reach 9.7 billion by 2050, the world faces unprecedented challenges; the ever-increasing demands for resources, rapid urbanisation, and the intensifying effects of climate change will further strain our planet's systems and societies. Yet, I am observing countless pressured and unsustainable systems worldwide — e.g., deforestation of the Amazon Rainforest, plastic waste in the Northern Pacific Ocean, and the Cape Town water crisis, among many others. Hence, the need for sustainability through effective regulations and interventions has never been greater. Such a societal response requires objective and transparent policy- and decision-making.

This dissertation, as well as its underlying research programme of SALTISolutions, serves this objective by expanding the knowledge on saltwater intrusion and applying this to solutions that improve freshwater availability while considering other stakeholder interests. More specifically the research reported here contributes to this by proposing a method to quantify the performance of water transport in estuaries. Such a method does not yet exist. Through this method, waterborne transport interests can now be taken into account more realistically in system-scale multi-objective trade-offs that are an inevitable part of estuarine decision-making. The work presented here is crucial since measures to promote the water transport function can have a significant impact on other functions in the system, and vice versa. Although this dissertation alone is not able to overcome the highly complex challenges that the world is facing, it provides an important step forward, with a framework and underlying methods that are readily available and expandable to be used in complex policy- and decision-making.

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Floor Pieter Bakker
Delft, November 2024

Prologue

Before this PhD research, my academic interests were primarily focused on the technical aspects of hydraulic modelling. Having completed my Master's degree in Hydraulic Engineering, I was captivated by the intricate dynamics of estuaries and the potential of numerical models to unravel them. Despite my initial aspirations to continue pursuing this research, circumstances led me to a different path, namely this PhD research. Little did I know that it would challenge my preconceived notions about the role of Hydraulic Engineering.

Dedicated to an ever-more sustainable world

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Introduction

1.1 Background

Globally, an estimated 240 million people live in river deltas (IIED, 2023). Here, socioeconomic developments (Loucks, 2019) and climate change (IPCC, 2023) pose acute challenges to the existence of major urban areas (Kuenzer and Renaud, 2012). Swift societal action is needed to overcome these challenges, which requires rational and transparent policy and decision-making (Peirson *et al.*, 2015).

1.1.1 Highly urbanised deltas and estuaries

Deltas are formed at estuaries, where the freshwater of rivers meets the salty water of the oceans. They provide many benefits to humans (Barbier *et al.*, 2011) and other forms of life (J. W. Day *et al.*, 2012) — e.g., plants, benthos, fish, birds, and mammals — and have consequently been attractors for them (Lotze, 2010). Deltas often contain fertile plains with access to freshwater, which are excellent for agriculture and settlements (Maul and Duedall, 2019). In addition, estuaries form an open connection to the sea that is often sheltered from rough marine conditions (J. H. Day, 1959). These calm and nutrient-rich waters with gradual salinity gradients have resulted in one of the most productive and biodiverse habitats (Breine *et al.*, 2011; J. W. Day *et al.*, 2012; Tangelder *et al.*, 2017).

Over time, many deltas around the world have developed into highly urbanised areas with large numbers of inhabitants (Maul and Duedall, 2019). These people need goods and services that are essential for their livelihood, such as freshwater (Wada *et al.*, 2011) and food (Beardsworth and Keil, 1996). In addition, they require luxury goods and services, such as shelter, clothing, and leisure (Sorinel, 2012). Consequently, agriculture has expanded and intensified (Totino *et al.*, 2024; Bosma *et al.*, 2005), requiring more and more freshwater (Jeuken *et al.*, 2016). Starting in the early 19th century, deltas have increasingly industrialised (Gu *et al.*, 2011; C. Yang, 2012; Loucks, 2019). To enable the import and export of consumer and capital goods, major seaports have been constructed in sheltered estuarine waters. They form crucial nodes in an extensive global transport network (see Figure 1.1), which facilitates the link between maritime transport and inner-city connections, thereby fostering prosperity (van Koningsveld *et al.*, 2023).

1.1.2 Nautical traffic and other stakeholders in deltas

The increase in the deltaic population, along with their developing needs, living standards, and ecological perceptions, has led to increased conflicts of interest between stakeholders competing for the same physical user space.

Waterborne transport is a major stakeholder in river deltas (Dooms *et al.*, 2013; Eskafi *et al.*, 2019), as the world's economy heavily relies on this effective and economical way of transporting cargo over large distances (Merk and Notteboom, 2015). More than 80% of the global trade volume is transported through seaports (UNCTAD, 2023). In addition, in some seaports, barge transport over inland waterways can contribute to more than 35% of the modal split of hinterland transport (Langenus *et al.*, 2022). Due to their connection to overseas

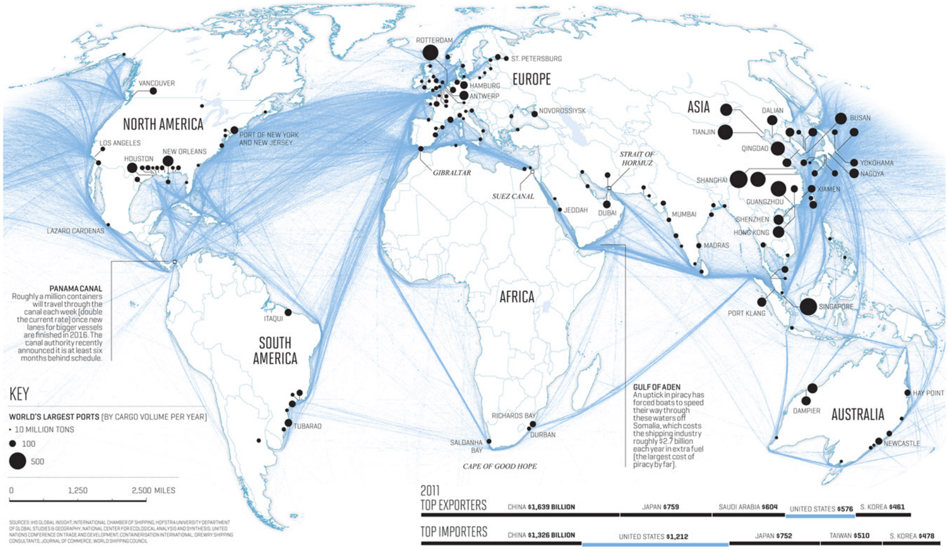

Figure 1.1: A world map of major seagoing traffic routes between the largest global seaport hubs. Many of these seaports are located in highly urbanised estuaries. *Figure by Nicolas Rapp.*

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and hinterland networks, seaports represent a substantial economic value to the regions in which they are located (Mudronja *et al.*, 2020). When the same hinterland can be served by different seaports, these ports compete with each other for the available cargo (Sdoukopoulos and Boile, 2020). In such cases, efficiency is a key performance indicator for seaports, which means that waiting times for vessels must be limited and ports must be accessible (Talley, 2006; Ducruet *et al.*, 2014). Extreme water levels, storms, waves, and currents can disrupt port operations, negatively influencing port efficiency (Camus *et al.*, 2019; Wiegel *et al.*, 2021). In the last 40 years, global cargo transport volume has tripled in size (UNCTAD, 2023). Driven by the principles of economies of scale, massive investments have been made in larger and deeper-draughted vessels and subsequently in more extensive port and waterway infrastructure to accommodate these vessels (Sys *et al.*, 2008). As vessel dimensions exceed the (natural) dimensions of port infrastructure, seaports have been subjected to expansion and deepening (Ramos, 2014). Since access channels and waterways are important elements of coasts and estuaries (Siemes *et al.*, 2023), these changes to the physical system can, in turn, put stress on the estuarine system and the stakeholders that rely on its functions.

Other major stakeholders in river deltas are local communities, water managers, and environmental groups (Knowles and Myatt-Bell, 2001), which, like waterborne transport, all depend on the physical environment (see Figure 1.2), such as the interactions between hydrodynamics, morphodynamics, and ecology (Wolanski, 2019). Their objectives typically involve freshwater availability, water safety, social-cultural well-being, and protection of ecological values (Vugteveen *et al.*, 2014). The performance of these stakeholder interests constantly varies over time due to changing environmental conditions and anthropogenic interventions (Borchert *et al.*, 2018; Yin *et al.*, 2020; Cox *et al.*, 2022a; J. Lee *et al.*, 2024).

1.1.3 Open and closed systems

From a system perspective, estuaries can be categorised into open and closed systems. This is shown in Figure 1.2. Open systems are considered semi-enclosed estuaries that have an open connection to the sea.

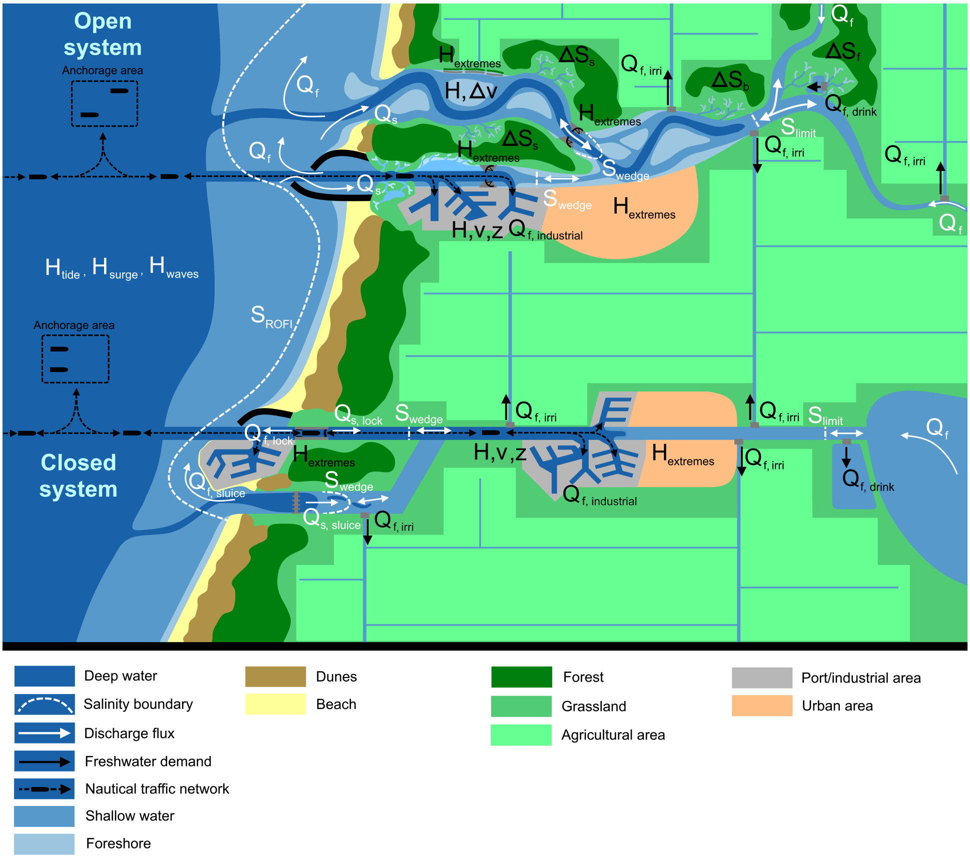

Figure 1.2: A schematical overview of a delta with an open (top) and closed (bottom) estuarine system and the connections between these environments and their main stakeholders (see text for more details)

In these systems, there are many dependencies between stakeholders and estuarine hydromorphodynamics (French *et al.*, 2016). Herein, water level (H), current velocity (v), discharge (Q) and salinity (S) are important hydrodynamic properties, while bed level (z) is an important morphodynamic parameter. For example, nautical traffic requires sufficient water depth and limited current velocities (Lemon *et al.*, 2003). River runoff in this system is naturally discharged under the influence of tides (H_{tides}), waves (H_{waves}) and storm surges (H_{surge}), the latter of which pose a threat to water safety ($H_{extremes}$) (Temmerman *et al.*, 2013). Saltwater is naturally present in an estuary due to complex hydrodynamic processes, which are primarily affected by river runoff (Q_f) and tidal mixing (H_{tide}) (Geyer and MacCready, 2014). Prolonged exposure to saltwater (Q_s) can lead to freshwater shortages for communities, namely drinking water ($Q_{f,drink}$), agriculture ($Q_{f,irri}$), and industrial cooling and processing water ($Q_{f,industrial}$) (Wada *et al.*, 2011). In addition, it can damage vegetated areas in the brackish and freshwater zones (ΔS_b and ΔS_f) (Sutter *et al.*, 2015). The inland extent of salinity (S_{limit}) and its vertical salinity structure (S_{wedge}) are prone to environmental dynamics and extremes, such as tides with spring-neap cycles, storms, and droughts (Haddout *et al.*, 2019). At sea, the river discharge creates a freshwater plume (S_{ROFI}) (Simpson, 1997; de Boer *et al.*, 2009). Saltwater ecology — e.g., at tidal flats and salt marshes — is affected by water levels (H) and current velocity gradients (Δv) (Zhou *et al.*, 2022). The population is another stakeholder that strives for social and cultural well-being, such as recreation at beaches, rivers and lakes, and limited nuisance near ports (Ghermandi *et al.*, 2010). In contrast, closed systems are former estuaries or emissaries that have been closed off using a hydraulic structure (e.g., man-made canals). To facilitate nautical traffic, navigation locks have been constructed. Although tidal dynamics are absent in such closed systems, river discharge (Q_f) has to be discharged by a sluice complex ($Q_{f,sluice}$). Despite this, a closed system can be prone to the influence of saltwater intrusion ($Q_{s,sluice}$ and $Q_{s,lock}$) and freshwater losses ($Q_{f,lock}$) by the operation of these infrastructures. Once saltwater intrudes into a closed system, flushing it back to sea can be challenging (Ebrahimierami *et al.*, 2021).

1.1.4 Current challenges

Progressive urbanisation and industrialisation have put constant pressure on the estuarine functions, potentially leading to conflicts between stakeholders' interests. On the one hand, this is caused by the societal response to these stressors through anthropogenic interventions, such as land reclamations for socioeconomic benefits (Cheng *et al.*, 2020), closure of estuaries for water safety (Figueroa *et al.*, 2022; Orton *et al.*, 2023), deepening of channels to improve waterborne transport performance (Johnson *et al.*, 1987; Best, 2019), maintenance dredging (Donázar-Aramendía *et al.*, 2018), and creation of freshwater buffers for freshwater availability (Tönis *et al.*, 2002; Morris, 2013). On the other hand, climate change has created challenging environmental conditions, such as higher water levels due to sea level rise and reduced freshwater input from the river due to more frequent and prolonged droughts (Z. Yang *et al.*, 2015). This has led to a situation where the increasingly conflicting stakeholder objectives can often no longer be fully satisfied (Ruiz *et al.*, 2014), posing challenges for policy and decision-makers who face complex trade-offs (Lubell, 2004).

The above challenge particularly holds in systems where waterborne transport interests generate major economic value, which is further highlighted in the next section. This stakeholder often requires system-scale interventions to remain viable under changing conditions and should be objectively included in policy and decision-making. For this, an underlying framework should be able to quantify the impacts of changes to the physical system on water transport performance. However, such a framework seems to be lacking, making rational policy and decision-making a challenge.

1.2 Real-world examples

To further highlight the above challenge, this section presents the following real-world examples that illustrate the trade-off between waterborne transport performance and freshwater supply in open and closed systems. They focus on how recent developments in physical systems have exposed the conflicting interests of stakeholders, and how underlying feasibility studies and Environmental Impact Assessments (EIAs) struggle to support objective and transparent policy and decision-making.

1.2.1 The Rhine-Meuse Delta, The Netherlands

The Rhine-Meuse Delta (RMD) is a heavily engineered estuary, comprising both open and closed systems.

Open system: the Nieuwe Waterweg — Port of Rotterdam

The Nieuwe Waterweg (NWW) forms an open system in the RMD that discharges most of the run-off from the Rhine River and simultaneously forms the gateway to the inland basins of the Port of Rotterdam (PoR). In 2019, the channel was deepened by 1.7 m to 16.4 m to improve port performance; a project that was granted based on a feasibility study and EIA by Arcadis (2015).

The feasibility study included a macroeconomic cost-benefit analysis that indicates the expected benefits for the PoR resulting in nearly 4 billion euros in net present value. The main benefits of the deepening were estimated to lie in a reduction of transport costs through improved port accessibility, enhanced flexibility on terminal choice, and, consequently, efficiency of cargo transfers. However, based on the validation of the cost-benefit analysis of the project by Wortelboer-van Donselaar and Francke (2016), the positive outcome was highly sensitive to the assumptions made — i.e., a projected increase in liquid bulk cargo and vessel size through customer acquisition by providing conditions that are more competitive than nearby ports. These numbers were provided by the PoR itself, some of which, according to the validation study, were not substantiated publicly due to the confidentiality of the underlying data. The subsequent reduction in transportation costs for the new fleet composition was not validated using a nautical traffic model.

In addition, the EIA quantitatively assessed impacts on other stakeholders' interests based solely on results from simplified methods. These briefly quantified the expected stresses of the deepening on the socioeconomic and ecological estuarine functions, most of which were expected to be neutral. In particular, the impact on freshwater availability was assessed as slightly negative. This impact was derived based on salinity concentrations near water intake stations, which were quantified using a simple hydrodynamic model without including the overall freshwater system and long-term socioeconomic developments and climate change (Svašek, 2014). A similar approach was used to evaluate the increase in emissions based on statistical indicators (Wortelboer-van Donselaar and Francke, 2016) and the impacts on ecology. This process resulted in cost estimations for further research on mitigation measures against saltwater intrusion, and costs for the expected increase in CO_2 emissions and deteriorating air quality. The unknown origin and unclear objective of these costs do not appear to transparently and rationally represent these stakeholder interests.

The EIA judged that salinity monitoring and water management measures — i.e., upgrading the alternative freshwater supply system — would reduce the aforementioned minor negative impacts on freshwater availability. Although this alternative freshwater supply system was eventually upgraded, the EIA did not address whether this would be resilient; it remains questionable whether the increased demand for upstream freshwater could be supplied during droughts given the drought projections for the estuary. Consequently, a severe drought in 2022 posed challenges to this system, since freshwater had to be shared with many upstream stakeholders (Hendriks and Mens, 2024). These unforeseen challenges remain if the trade-offs between waterborne transport and other stakeholder interests are not explicitly quantified on a system scale. Such an approach would require a system-scale framework that explicitly links the waterborne transport function with other user functions, which was not addressed in the EIA.

Closed system: the sea lock complex at IJmuiden — Port of Amsterdam

The North Sea Canal (NSC) is a waterway constructed to link the Port of Amsterdam (PoA) with the North Sea, forming a closed system in the RMD. A navigation lock complex was built at the seaward end of the canal, which has expanded over time based on updated requirements for vessel size and nautical traffic capacity. The operation of these navigation locks causes saltwater intrusion into the NSC (van der Baan *et al.*, 2023). In 2022, a new large sea lock with a length of 500 m, a width of 70 m, and a depth of 18 m became operational, which was constructed to replace the previous largest sea lock of the complex, which had a length of 400 m, a width of 50 m, and a depth of 15 m. The previous lock was built in 1929 and was at the end of its lifetime, causing frequent disruptions due to breakdowns and required maintenance. Before granting this project, a feasibility study and EIA were commissioned by Rijkswaterstaat (2014). In these studies, the benefits of a new, larger navigation lock were based on assumptions that the trend of nautical traffic through the lock complex would continue to increase, in tandem with vessel size. A study by Royal HaskoningDHV (2014a) showed that, based on this prognosis, the capacity and dimensions of the existing locks would be surpassed — i.e., vessel size would exceed those that could safely pass through the lock, and the traffic intensity would lead to congestion with significant vessel delays. Therefore, it was feared that the PoA would become increasingly inaccessible and inefficient, threatening its future function. The ultimately selected lock dimensions increased the capacity of the lock complex, allowed vessels with larger beams (up to 57 m, an increase of 12 m) to be levelled, and enabled the handling of the deepest-draughted vessels (of 13.75 m of draught) during ebb tide.

The EIA included a simplified study of saltwater intrusion, which estimated that the construction of the new sea lock would increase intrusion, thereby impacting freshwater quality for users (Royal HaskoningDHV, 2014b). Comparable studies have shown the uncertainty in predicting the main source term of salt: the lock operations (Augustijn *et al.*, 2011; Wijsman, 2013; Noordman, 2016; O'Mahoney *et al.*, 2022). Nevertheless, the EIA mentioned —without explicitly quantifying— that this threat could be fully mitigated by a combination of local infrastructural countermeasures at the lock and increased upstream flushing discharge from the Rhine River. Since the system-scale effects for the freshwater supply system appear not to have been addressed, the resilience of the latter measure can be questioned; the additional freshwater required from the Rhine River may be used elsewhere, i.e., for consumption or to counter saltwater intrusion through the NWW at the PoR (as shown in the previous example). Based on further research after the grant of the project, it was decided to build a selective withdrawal structure as a local infrastructure countermeasure against saltwater intrusion. According to expectations, this measure enables a more efficient discharge of intruded seawater from the canal, thereby reducing the severity of the saltwater intrusion problems (Verbruggen and van der Baan, 2022). The countermeasure is planned to be operational in 2025.

As the new lock opened before the operation of the selective withdrawal, an extreme drought in 2022 caused severe impacts on waterborne transport performance. Hendriks and Mens (2024) reported that the number of lock operations of the existing lock had to be strictly reduced by clustering as many vessels as possible into the same lock operation, causing severe vessel delays. Furthermore, they stated that substantial amounts of upstream flushing discharge were required, which proved to be a huge challenge given the needs of other freshwater users, e.g., the alternative freshwater supply to mitigate the effects of the deepening of the PoR. As the effectiveness of the selective withdrawal structure is uncertain (Pouwels *et al.*, 2024), less optimistic functioning could require additional operational countermeasures and significantly more freshwater upstream for flushing. Such system-scale risks were omitted in the EIA, as the trade-offs between waterborne transport and other stakeholder interests have not explicitly been quantified on a system scale. As for the PoR case, a system-scale trade-off framework and underlying methods to assess this appear to be lacking.

1.2.2 International cases

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Complex decision-making in pressured systems does not only occur in the RMD but is a global challenge.

Open system: The Hudson and Delaware River Estuaries, United States of America

The Hudson and Delaware River Estuary host the Ports of New York and New Jersey, and the Ports of Philadelphia and Wilmington, respectively. In the Hudson River Estuary, vessels navigate through the waterways in the Lower and Upper New York Bay and The Narrows to access the port basins from the Atlantic Ocean. These waterways also form the estuary's mouth. Hoagland *et al.* (2020) show that New York City's main demand for freshwater is supplied by underground aqueducts that traverse the catchment areas of the Hudson and Delaware Rivers within the State of New York, connecting upstream reservoirs with the city. In contrast, in upstream cities, such as Poughkeepsie (120 km from the mouth), freshwater primarily originates from surface water extraction from the Hudson River. The total demand for drinking water competes with other freshwater users, such as hydropower from dams on the Hudson River, as well as ecological needs, tourism, and recreation, while ensuring water safety. In the Delaware River Estuary, the surface water of the Delaware River provides part of the drinking water of Philadelphia, Pennsylvania, which is extracted 177 km from the mouth.

The Hudson and Delaware River estuaries are susceptible to saltwater intrusion, which is exacerbated during droughts. Hoagland *et al.* (2020) state that Poughkeepsie has experienced several prolonged interruptions in surface water extraction over the last decades. In addition, a severe dry period from 1961 to 1967 caused a near collapse of the drinking water supply of Philadelphia, when the tip of the saltwater intrusion almost reached the extraction locations. This was partly due to the limited discharge from the emptied upstream drinking water reservoirs in the state of New York. Consequently, an adaptive management process was established in 1971 that guarantees a minimum flow in the Delaware River. However, Hoagland *et al.* (2020) expect that, during a severe drought, future compliance with this process may lead to a deficit in the freshwater supply of New York, given its continuing increase in demand. To combat this, the only additional source of freshwater is surface water from the Hudson River, which can only be extracted from a location downstream of Poughkeepsie, an area affected by saltwater intrusion.

To make matters even more challenging, over the last 25 years, the Hudson and Delaware River Estuaries have been deepened by 1.5–3.0 m to 13.7 and 15.2 m, respectively. This increased the flux of saltwater intrusion (Dolgopolova, 2014; Chant *et al.*, 2018; Ralston and Geyer, 2019; Pareja-Roman *et al.*, 2020). The last deepening projects, in 2014 and 2016, respectively, were primarily driven by a 'race to the bottom' between the competitive Port of Philadelphia and Ports of New York and New Jersey, given the expansion of the Panama Canal in 2016 (Rodrigue, 2024) (as shown in the next example). This expansion allowed the transit of vessels with a maximum draught of 15.2 m bound from the Pacific Ocean to ports on the West Coast of the United States of America. There are plans to further deepen both aforementioned ports by a further 1.5 m (Port of New York and New Jersey, 2019; Port of Philadelphia, 2024).

According to Hoagland *et al.* (2020), feasibility studies and EIAs on the deepening projects primarily focused on the cost-benefit analysis of the economic gains and losses. The researchers describe this as oversimplified, as other external environmental effects were not included in this analysis. For the feasibility study and EIA of the deepening of the Port of New York and New Jersey to 16.8 m (U.S. Army Corps of Engineers, 2022), the potential negative effects on saltwater intrusion are omitted. Moreover, the EIA concludes that, without providing substantial model results, effects on ecology will be minor. Meanwhile, Osborne *et al.* (2014) report a potential threat of salinity intrusion into the brackish wetlands in the Hudson River. In addition, Hoagland *et al.* (2020) expect that a sequence of dry years, such as between 1961 and 1967, can cause severe impacts on the freshwater supply of New York and/or Philadelphia. In conclusion, it appears that, also in this example, the EIA lacks a holistic and transparent approach to quantify the impacts of physical system modifications on stakeholders' interests.

Closed system: The Panama Canal

The Panama Canal is a waterway that offers a shortcut for seagoing vessels between the Pacific and Atlantic Oceans. The passage consists of the freshwater reservoir of Lake Gatún, connected through lock complexes with both oceans, forming a closed system. The reservoir's freshwater is used for multiple objectives: navigation lock operations, agriculture, drinking water, and hydropower, on which more than 2 million Panamanians depend. The supply of this water is frequently disrupted during droughts, which periodically occur during El Niño cycles.

Due to the earlier-mentioned increase in traffic volume and vessel size, the Panama Canal Authority (PCA) feared the potential loss of functionality of the Canal due to limited lock capacity and dimensions. To mitigate these risks, the PCA proposed building a third set of larger locks, expanding the canal's transport capacity and efficiency, and facilitating the passage of larger-sized vessels. In 2016, after an EIA, permits were granted for the project. The Panama Canal Authority (2017) claimed that this recovered its market share. However, serious concerns were raised about the technocratic and non-transparent nature of the EIA (Gonzalez, 2008), which failed to explicitly quantify the impacts of the new lock complex on socioeconomic and ecological stakeholder interests.

During the severe droughts of 2015 and 2023 caused by El Niño, the water level of the lake dropped significantly. Such droughts put pressure on freshwater availability and power supply and also disrupted vessel traffic, as lock operations had to be reduced and draught limitations installed (Larsen, 2019; Calvo Gobbetti and Ríos Córdoba, 2024). In 2023, this caused vessel delays of over 6 days with queues of more than 200 vessels, contributing to significant economic losses (Bird and Ogunsakin, 2024). Paradoxically, data presented by Calvo Gobbetti and Ríos Córdoba (2024) indicate that the severe drop in water level during these droughts is, among other causes, triggered by the operations of the larger locks that consume a lot of freshwater. They explain that the water-saving basins of the navigation lock chambers are often not used, as this promotes saltwater intrusion into the system given the many lock operations. As climate change and socioeconomic trends may pose further challenges in the future, their research assesses the impacts of plans to expand existing reservoirs and construct new ones to combat the low water levels during droughts on canal passage reliability for the deepest-draughted vessels. Such plans highlight the importance of the need for rational policy and decision-making that can explicitly quantify impacts on waterborne transport and other stakeholder interests, for which a system-scale trade-off framework and underlying methods are seemingly lacking.

1.3 Problem statement

Based on the aforementioned examples, it can be recognised that stakeholder competition in highly developed and urbanised deltas requires rational policy and decision-making. However, a system-scale framework that can quantify the trade-off between the interests of waterborne transport and other freshwater users is currently lacking, inhibiting such policy and decision-making. This is not limited to the above examples, as there are countless examples where conflicting stakeholder interests have led to similar decisions: the Mississippi Delta (Johnson *et al.*, 1987), the Pearl River (Yuan and Zhu, 2015), the Yangtze River (Q. Chen *et al.*, 2019), Chesapeake Bay (Bastian, 1980), the Scheldt Estuary (Cox *et al.*, 2022b), Canal Ghent-Terneuzen (Biemond *et al.*, 2024b), Mekong Delta (Nguyen and Le, 2023), Lake IJssel (Weiler, 2019), and many more. The problem statement for this dissertation is therefore twofold: (1) the lack of a framework to quantify the system-scale waterborne transport performance as a function of the physical environment, and (2) how this lack inhibits the rational trade-off between impacted stakeholder interests when considering interventions in systems where waterborne transport plays a significant role.

1.3.1 The knowledge gap

To aid objective policy and decision-making, valuable contributions have been made to the literature, in different fields of research.

In integrated water resource management, conflicting water use between multiple stakeholders is assessed using robust decision-making approaches based on hydro-economic modelling frameworks. Eamen *et al.* (2021) performed this for the West Canadian Saskatchewan River Basin, while Nikolopoulos *et al.* (2022) considered an anonymised urban freshwater supply system. Furthermore, a hydroecological modelling framework was developed by Kragt (2013) to calculate socioeconomic and ecological outcomes for different land use scenarios in Tasmania, Australia. Integrated coastal flood assessment is another field of research where multi-stakeholder interests are quantified. For example, Kind (2014) calculated the monetary costs and benefits of the Dutch flood protection system, using multiple risk factors. Coelho *et al.* (2020) also performed a monetary cost-benefit analysis using model output for coastal areas. In a broader stakeholder context, Townend *et al.* (2021) developed a macroscopic coastal model for the English Coast, where resilience is calculated by including socioeconomic and environmental perspectives.

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In contrast, integrated coastal zone management often assesses the impacts on stakeholder interests qualitatively. Here, highly complex interactions between the natural services and multi-stakeholder interests are present. Moreover, the stakeholder interests are often dissimilar and not quantifiable in monetary units and therefore not directly comparable, for example, the ecological value of estuaries. Various researchers have made efforts, using distinct frameworks with different underlying methods. A metamodel-based assessment framework was presented by Holman *et al.* (2008), quantifying stress indicators of agriculture, water resources, biodiversity, and coastal and river flooding given socioeconomic developments and climate change. Garmendia *et al.* (2010) applied an expert-based multi-criteria evaluation of socioeconomic stakeholder interests for different estuary layouts for the Spanish Urdaibai Estuary. The Millennium Ecosystem Assessment framework was adopted by Butler *et al.* (2013) to obtain trade-off correlation factors due to stresses on socioeconomic stakeholder interests and ecological functions, considering the effects of land use of the Tully–Murray River Basin on the ecosystem of the Great Barrier Reef. Cordier *et al.* (2011) developed a data-driven ecological-economic input-output model to calculate monetary benefits for different land use scenarios in the mouth of the Seine Estuary, including the Port of Le Havre. Moreover, Pinto *et al.* (2013) used the Drivers-Pressures-Status-Impacts-Responses Framework to establish quantitative relations between the competing socioeconomic stakeholder interests and ecological needs of the Portuguese Mondego Estuary. W. Yang *et al.* (2018) constructed trade-off curves for ecological performance indicators that are affected by land reclamation projects in the Yellow River Delta. A GIS fuzzy-set modelling approach was developed by Noble *et al.* (2021) to determine overlapping spatial socioeconomic and ecological needs for Port Stephens-Great Lakes Marine Park in Australia. Lastly, Hinkel *et al.* (2023) performed a multi-criteria analysis based on model indicators to derive qualitative impacts for the coastal reef flood protection of the Maldives.

However, very few comprehensive integral coastal zone management studies were found that explicitly quantified the trade-off between waterborne transport interests and other user functions. This is underlined by Pearson *et al.* (2016). In ports and waterways, only a few single-stakeholder optimisation studies were found. For example, to reduce vessel emissions, L. Jiang *et al.* (2014) performed a cost-benefit analysis, while Ölçer and Ballini (2015) created a framework based on fuzzy multiple attribute decision-making methods. Parrott *et al.* (2011) created a decision support system for the interaction of nautical traffic and whales in the Canadian St. Lawrence River Estuary. Moreover, a stochastic multi-criteria analysis was performed by García-Morales *et al.* (2015) to select the most effective layout of a hypothetical port, considering an increase in traffic and environmental interactions.

Beyond integral assessments, it was found that most research primarily focuses on quantifying the effect of nautical traffic on the properties of the physical system, rather than vice versa. Among other research, Prumm and G. Iglesias (2016) modelled the impact of port expansion on the morphodynamics of the Spanish Ribadeo Estuary, and van Dijk *et al.* (2021) the effect of deepening on the mudflat stability. Conversely, limited research was found on the impact of natural and man-made changes to the physical system on waterborne transport from a system perspective and in relation to other user functions. Almaz and Altiok (2012) studied the effect of channel deepening on vessel delays in the Delaware River, while Izaguirre *et al.* (2020), and Meyers and Luther (2020) specifically for Tampa Bay, U.S.A., focused on the effect of climate change on port performance.

Moreover, in general, the above literature focuses on open systems. In the context of closed systems, an even larger lack of framework and underlying methods is found. Liang *et al.* (2014) developed a hydroenvironmental, semi-empirical model to predict water quality in canal systems with weirs and navigation locks. Augustijn *et al.* (2011) modelled saltwater intrusion due to navigation lock operation in the Dutch Mark-Vliet Canal. Furthermore, Weng *et al.* (2020) modelled the effect on the estuarine hydrodynamics for a proposed discharge sluice in the Jiaojiang River Estuary in China, which neglected the effects of the navigation lock operation.

1.3.2 Consequences of the gap

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Based on the literature reviewed, it can be concluded that there is a notable lack of decision-making frameworks with underlying methods that quantify waterborne transport performance as a function of the physical environment. This inhibits the rational trade-off between impacted stakeholder interests for interventions in systems where waterborne transport plays a significant role. Following the current qualitative approach can fuel conflicts in cases where the argued economic benefits of trade need to be weighed against equally important system functions such as drinking water availability, agriculture, etc. Quantifying these impacts and valuing them through stakeholder engagement is required for objective and transparent policy and decision-making (Hagen *et al.*, 2017; Chakraborty *et al.*, 2023).

The earlier mentioned EIAs, like Arcadis (2015) for the deepening of the NWW and Rijkswaterstaat (2014) for the new sea lock at IJmuiden, provide a clear demonstration of the identified knowledge gap. Without being able to quantify explicit trade-offs between system-scale stakeholder interests, the EIAs give the impression of subjectivity and non-transparency. While these shortcomings do not mean that the decisions taken are necessarily erroneous, the resulting decisions and proposed designs can be suboptimal. In other words, proposed system interventions may lead to unanticipated adverse effects that may not be acceptable or resolvable by mitigation measures, monitoring, and/or adaptive management. Moreover, during severe circumstances, even the nautical traffic, for which the interventions were designed in the first place, could be adversely impacted, as was observed for the PoA and Panama Canal.

1.4 Research objective and scope

Therefore, this dissertation's main objective is to (1) assemble a quantification method to quantify waterborne transport performance as a function of the physical environment, and (2) explore how this method can be incorporated into a framework that can quantify rational trade-offs between impacted stakeholder interests for interventions in systems where waterborne transport plays a significant role. The resulting framework and underlying methods intend to overcome the presented shortcomings in EIAs to aid objective and transparent policy and decision-making in estuaries.

This dissertation focuses on estuaries where waterborne transport is a major stakeholder. Thereby, primarily seagoing traffic is considered, as the associated vessels are typically dominant in the decisions related to infrastructure dimensions. Furthermore, the dissertation will focus on how changes to the physical system affect waterborne transport on the one hand and freshwater availability on the other. Although this is not the only concern in the management of estuaries, it is a significant trade-off that is experienced in many estuaries around the world (see Section 1.2). The focus on seagoing vessels and freshwater availability is needed to create a focus for this dissertation, but it is believed that the developed trade-off framework can also be applied to other trade-offs. These include trade-offs regarding water safety, ecology and port performance (van den Bergh *et al.*, 2005), and even in cases where waterborne transport is not a stakeholder, such as in the context of ecology and discharge sluice operations (Brunink and Hendrickx, 2024). Moreover, the trade-off framework and underlying methods can also be applied to other types of systems where waterborne transport is a major stakeholder, such as inland waterway networks of barge transport (e.g., Rhine-Alpine and Yangtze Corridors), inland seagoing traffic (e.g., Río Paraná), and offshore seaports (e.g., Port of Algeciras).

1.5 Research questions and methodology

The posed objective and scope led to the following research question: *To what extent can the interests of waterborne transport performance be incorporated into more objective policy and decision-making?*

To answer this research question, this dissertation follows a two-step approach. First, a method will be established that can quantify the impact of changes to the estuarine system on waterborne transport. Second, a framework will be assembled that can evaluate multi-stakeholder interests for an intervention in the estuary through quantification of a trade-off curve between the impacts on the stakeholders' Key Performance Indicators (KPIs), including waterborne transport, estimated by the established quantification method from the first step. This approach is underlying the following sub-questions (SQs):

SQ 1. *How effectively can existing methods assess the waterborne transport performance by quantifying its underlying interactions with the physical system?* (Chapter 2)
A literature study is conducted to determine how the interests of waterborne traffic in estuaries can be quantified through key performance indicators. This study is furthermore used to identify the key interactions between seagoing nautical traffic and the physical environment. Using these key processes, criteria are derived to evaluate existing quantification methods. This results in a method that is most suitable for assessing the impacts on waterborne transport performance in estuaries, although it may require further improvements.

SQ 2. *How can the most suitable quantification method be enhanced to more extensively include the interactions between waterborne transport and the physical system?* (Chapter 3)
Potential shortcomings of the existing quantification methods are resolved by further developing the most suitable method, found in Chapter 2. Idealised test cases are conducted with implementations of the enhanced quantification method to demonstrate its functionality and applicability to real-world case studies.

SQ 3. *How accurately can the implemented quantification method replicate waterborne transport performance?* (Chapter 4)
To make accurate assessments, the further developed quantification method should be implemented as a nautical traffic model, and validated with real data. For this, a hindcast study is performed to mimic the observed behaviour of seagoing traffic bound for/from an inland sea terminal in the PoR for the year 2019. Vessel waiting times are selected as the KPI, based on findings in Chapter 2. This indicator is calculated with both the modelled and observed data, from which a comparison can be made to show the accuracy of the nautical traffic model and confirm the validity of the quantification method.

SQ 4. *How can the interests of waterborne transport be objectively weighed against other stakeholder interests in more objective policy and decision-making?* (Chapter 5)
To include the validated quantification method in decision-making challenges, a framework is developed and applied to quantify the trade-off between freshwater availability and performance of the PoR. Hereby, it is intended to quantify how bed level affects both stakeholder objectives.

The answers to the above sub-research questions will result in the answer to the main research question, which forms the conclusion of this dissertation (Chapter 6).

2

Quantifying the interactions between waterborne transport and the estuarine system

The more you know,
the more you realise how much you don't know.

Socrates

Based on Chapter 1, one can observe that decision-makers are often unable to objectively and transparently quantify the impact of changes in the physical system on waterborne transport performance. This potentially results in suboptimal system interventions. It is hypothesised that this shortcoming can be resolved using a quantification method that can model the system-scale interactions between the waterborne transport system and the physical system. Therefore, the following question is raised (SQ 1): **How effectively can existing methods assess the waterborne transport performance by quantifying its underlying interactions with the physical system?** To answer this question, this chapter presents a literature study aimed at evaluating the suitability of existing methods. For this, criteria are derived based on the identification of the KPIs for waterborne transport, and an assessment of the interactions between the nautical traffic system and the physical estuarine system. Efficiency by measuring vessel waiting times is found to be the most suitable KPI to describe waterborne transport performance. Waiting time is primarily caused by downtime and congestion of port infrastructure. In open estuaries, tidal downtime is determined to be the main interaction between the nautical traffic system and the physical system. These interactions depend on water levels, current velocities, and Maintained Bed Levels (MBLs). Cascading waiting times can emerge from the interactions between tidal downtime and congestion, the latter of which is dependent on the capacity of the port and waterway infrastructure and services. In closed systems, the interactions between nautical traffic and the physical system involve navigation lock operations that can cause saltwater intrusion and freshwater losses. Although various analytical accessibility, simulation-based (i.e., micro-, meso-, and macroscopic) and data-driven quantification methods exist in the literature, none of the methods proves directly suitable to assess the impacts on waterborne transport performance. However, the mesoscopic quantification method implemented through the OpenTNSim library is found to be the most promising to overcome these shortcomings.

This chapter is based on excerpts from the conference papers and journal articles that form the basis of the subsequent chapters.

2.1 A key performance indicator for waterborne transport

Waterborne transport entails the movement of people and goods by vessels that sail over water to connect ports, resulting in nautical traffic. Ports are complex nodes in the supply chain, where payloads can be transferred between different modes of transport, and hence, have many different stakeholder groups (Notteboom and Winkelmans, 2019; Lind *et al.*, 2019). This signifies, already within the water transport domain, that system performance is multidimensional, meaning any aspect of the port and waterway system can affect stakeholders' interests in different ways (Ha *et al.*, 2019), such as operational dimension, customer perspective dimension, logistics-chain dimension, macro dimension (i.e., emissions and economic factors), and organisational dimension (OConnor *et al.*, 2019). Zis *et al.* (2023) found, related to shipping, that a social perspective dimension can be added, which, among other factors, relates to nautical safety.

For nautical traffic, which is affected by changes to the physical system, the economic perspective of the operational dimension is often considered to be the most important KPI (Bellsolà Olba *et al.*, 2017). This includes productivity and efficiency (OConnor *et al.*, 2019). Ports and waterway systems for seagoing vessels must be productive and efficient, to be viable and competitive (Slack *et al.*, 2017; Michaelides *et al.*, 2019). This means that throughput volumes have to be maximised (de Langen and Helminen, 2015), while vessel turnaround times have to be limited (Michaelides *et al.*, 2019; Mazibuko *et al.*, 2024). These performance indicators are interrelated, as there exists an optimum level of service where throughput is maximised with acceptable turnaround times (Talley, 1994).

Port and waterway efficiency is important for nautical traffic. For example, Duldner-Borca *et al.* (2023) found that for inland waterways, transport duration is one of the KPIs that determines transport costs. Zis *et al.* (2023) found that the most influential economic KPIs are related to time, such as cargo transport duration, and lock passage delay. Sant' Anna and Kannebley Júnior (2018) even quantified the impact of each additional hour of vessel delay on export reduction in 16 Brazilian ports. Moreover, the benefit of a system intervention such as the deepening of the NWW in 2019, was expressed in terms of transport cost reduction, which in turn was derived from predicted turnaround time reductions, namely by not having lightering operations and excessive tidal windows (Arcadis, 2015; Wortelboer-van Donselaar and Francke, 2016). For efficiency, vessel turnaround time can be a useful KPI (Ballis, 2004; Henesey, 2006; Dragović *et al.*, 2006). This is affected by waiting times (Morales-Fusco and Saurí, 2009; Michaelides *et al.*, 2019), which, from a nautical perspective, are frequently used as a KPI for ports and waterway systems (Yahalom and Guan, 2022).

2.2 The interactions between nautical traffic and the physical systems

Nautical traffic is affected by external conditions that result from the physical environment. Studies by Shu *et al.* (2017) and Bellsolà Olba *et al.* (2018) conclude that visibility, wind, water levels, and depth-varying current velocities can cause downtime and affect individual vessel behaviour, which in turn can result in system-scale effects, such as the collective effect of wind and currents on vessel speeds, and the effect of water depth-related loading rates on vessel trips and arrival rates. Such effects can lead to cascading effects for entire port and waterway systems (Vinke *et al.*, 2022; van Koningsveld *et al.*, 2023). From a systemic viewpoint, downtime can cause disruptions in port and waterway operations, leading to vessel waiting time (Moita *et al.*, 2016; Musisinyani *et al.*, 2020), and reduced vessel throughput (Na *et al.*, 2007), thereby affecting waterborne transport performance. Hence, such interactions are important to include in quantifying water transport performance as a function of the physical environment. In this dissertation, the main interactions between the nautical traffic system and the physical environment are limited to tidal downtime, including their cascading effects through congestion, and navigation lock operations.

2.2.1 Tidal downtime

To limit vessel waiting times, ports must be accessible from a nautical-logistical perspective (Talley, 2006). A nautically accessible port ensures the safe and efficient transit of the deepest-draughted seagoing vessels, preventing grounding (Bos *et al.*, 2011). Vantorre *et al.* (2014) explain that port authorities, to limit required dredging efforts and maximise revenues, use temporarily elevated water levels (i.e., increased water depths) during high tide to allow vessels to enter the port, thus enabling shallower MBLs. Their research presents that port authorities establish so-called tidal windows for this, which are tidal intervals during which deep-draughted vessels can access or leave the port. The MBL design results from the trade-off between nautical accessibility and dredging costs: the deeper the bed levels, the better the accessibility, but the higher the dredging costs, and conversely, the shallower the bed levels, the lower the accessibility, but the lower the dredging costs

Vantorre *et al.* (2013) make a distinction between vertical and horizontal tidal windows. They explain that vertical tidal windows are periods during which there is sufficient water depth when the actual draught of a vessel is smaller than the actual water depth. In many ports, this occurs when a vessel complies with the Under-keel clearance (UKC) policy based on PIANC (2014) (see Section 2.3). These conditions must hold throughout the entire route of the vessel. In addition, regarding horizontal tidal windows, they explain that the strength of tidal (cross–)currents during this interval should be limited to allow the vessel to safely manoeuvre into a port basin. Their research finds resulting accessible tidal windows as the combination of vertical and horizontal or current tidal windows, which generally occur around high water slack.

To apply this approach, Vantorre *et al.* (2013) explain that port authorities need to know the hydrometeorological conditions and the established MBL for this route. Furthermore, they present that the authorities require in advance an estimated time at which the vessel will pass certain sections of the waterway. The research shows that this results in different opening and closing times of particular sections of the waterway, from which the governing tidal windows can be calculated (see Figure 2.1). Applying this method, Vantorre *et al.* (2014) observe that outbound vessels experience shorter tidal windows than inbound vessels. This is caused by the tidal dynamics; an outbound vessel experiences shorter high waters as it sails against the direction of the tide.

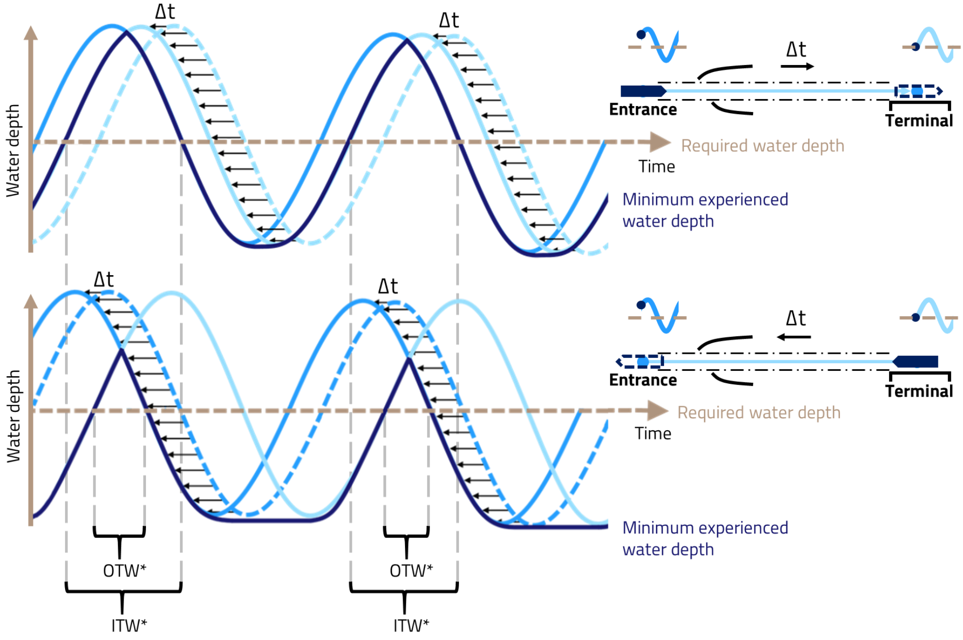

Figure 2.1: The calculation method for tidal windows as applied in the current design approaches for bed levels: *ITW: Inbound Tidal Window, OTW: Outbound Tidal Window.

Tidal downtime is considered to be the most common form of downtime, as many port and waterway systems in open estuaries are prone to mesotidal and macrotidal environments (Pilkey and Fraser, 1999). While downtime due to wind and waves (Hurdle *et al.*, 2009; Musisinyani *et al.*, 2020; Wiegel *et al.*, 2021) is also a common form of downtime in waterborne transport in offshore ports, it occurs less frequently in sheltered estuaries (J. H. Day, 1959; Scott *et al.*, 2016). Therefore, tidal downtime should be included in quantification methods for waterborne transport performance in estuaries.

2.2.2 Cascading waiting times: tidal downtime and congestion

Research by Du *et al.* (2015) shows that berth availability can interact with tidal downtime. They show that tide-bound vessels that have to wait on a tidal window can cause other non-tide-bound vessels to wait, leading to more berth congestion. These are so-called cascading waiting times. There are many other types of infrastructure and port services besides berths that can cause congestion, such as tug and pilot availability (Nikghadam, 2023) and yard storage (Talley and Ng, 2016). Hence, a quantification method should include these effects. For simplicity, this dissertation focuses solely on the congestion of wet infrastructure, such as anchorage areas, waterways, turning basins, and berths.

2.2.3 Saltwater intrusion through lock operations

In closed systems, the interactions between nautical traffic and the physical system include freshwater losses and saltwater intrusion fluxes, which are principally and directly caused by waterborne transport through navigation lock operations (Wijsman, 2013). The lock exchange fluxes are exchanged due to levelling and door-open phases of navigation locks (van der Ven *et al.*, 2015).

Various countermeasures can be taken at the lock to limit freshwater losses and saltwater intrusion fluxes (PIANC, 2021). Infrastructural countermeasures are bubble and water screens (Oldeman *et al.*, 2020), selective withdrawal of saltwater and flushing (O'Mahoney *et al.*, 2022) and water-saving basins (Calvo Gobbetti and Ríos Córdoba, 2024), which do not or only minimally impact vessel waiting times through prolonging levelling times. In addition, operational measures can be temporarily undertaken during droughts, such as a reduced number of lock operations and vessel clustering (Hendriks and Mens, 2024). These methods can severely impact vessel waiting times. Hence, navigation lock operations should be accounted for by a quantification method while assessing the impact of navigation lock operations on waterborne transport *and* the physical system.

2.3 The current design approach for maintained bed level designs

To implement tidal windows in port and waterway systems, a method reported by PIANC (2014) is frequently used. It applies safety margins to the concept of water levels, vessel draughts, and bed levels. These components are visualised in Figure 2.2 and are explained in this section. The conservative PIANC (2014) design approach results in MBL designs that are required for the dimensions of the deepest-draughted vessels to navigate port basins and waterways during a significant period over the tide.

The PIANC (2014) approach prescribes a minimum UKC to be kept for each vessel. This gross UKC is the difference between the measured draught of the vessel with respect to a specific MBL. The MBL is dependent on the design bed level. Hence, the design bed level may theoretically follow directly from the gross UKC and the measured draught of the deepest-draughted vessel. However, a *design water level* should be established for this purpose. These three components (i.e., MBL, UKC, and design water level) are discussed in the remainder of this section.

The MBL is a fixed level that is guaranteed to be above the actual bed level. It equals the channel dredge level, corrected by some safety margins. These allowances account for uncertainties in bottom-related factors, such as dredging, surveying, and sediment conditions. Additionally, there is a maintenance margin that provides a buffer for the sedimentation between dredging works.

A gross UKC is applied to the measured vessel draught to derive a maximum static draught, and subsequently a maximum dynamic draught. The static draught refers to the lowest level of the hull of a stationary vessel in calm saline water. The UKC is composed of a static and a dynamic component. It includes multiple margins that compensate for ambiguities in these components. Margins are applied that allow for uncertainties in the determination of this static draught (e.g.

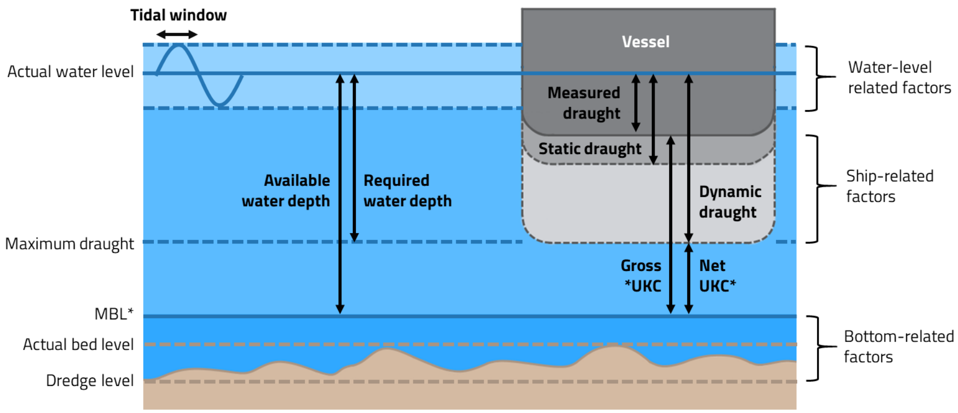

Figure 2.2: Overview of the relevant parameters in the design of the maintained bed level: *UKC: Under Keel Clearance, MBL: Maintained Bed Level.

hogging and sagging). Furthermore, an extra margin is required, called the Fresh Water Allowance (FWA), to account for additional static draught due to a decrease in the density of water over the route — e.g., due to salinity and water temperature variations.

The maximum dynamic draught is dependent on the complex interactions of a moving vessel with its surroundings (e.g. wind, hydrodynamics, and infrastructure). These dynamics influence the motion of a moving vessel, and thereby its draught. Examples include motion responses due to waves, vessel-waterway interactions (e.g. squat and dynamic trim), and wind and turning (e.g. dynamic list and heel). Extra margins are added to account for these motions. Finally, an additional allowance, called the Net UKC, is applied. This component can depend on the type of sediment and vessel, as well as the environmental consequences of a vessel hitting the bed. The gross UKC is the sum of all these margins. It must be greater than a certain Manoeuvrability Margin (MM), which ensures that a vessel has adequate manoeuvrability. According to PIANC (2014), the MM is the difference between the available water depth with respect to the MBL minus the static draught and the dynamic components of heel, squat, and trim.

Water levels are subject to fluctuations that must be taken into account. These are mainly caused by waves, tides, and meteorological influences, such as surges and seiches. The additional margins can either be positive or negative. Allowances for shorter-term seiches, waves and meteorological effects are mainly 'negative' for port accessibility — i.e., they lower the required bed level — as they account for their potential to lower the water levels. In contrast, longer-term tides generally can result in a 'positive' contribution to the bed level (i.e. they elevate the required bed level), since they temporarily increase the water level throughout the route of the vessel.

2.4 Assessment criteria for quantification methods

In Section 2.1, it was found that waiting time is the key performance indicator for assessing the impact of physical system changes on nautical traffic. Moreover, in Section 2.2, it was found that cascading effects between tidal downtime and the congestion of wet infrastructure govern the interactions between the nautical traffic system and the physical system. For this, tidal water levels, current velocities and MBLs are important (see Section 2.3). For closed systems, these interactions also entail saltwater intrusion fluxes and freshwater losses during levelling and door-open phases of navigation locks (see Section 2.2.3). To assess the impact of changes to the physical system on the waiting time of vessels, a quantification method should be employed that can resolve these processes in various systems and problem contexts. Based on these findings and the objective of this dissertation, criteria have been derived, to which the quantification method should adhere. The criteria can be subdivided into three categories, namely criteria that are required for the quantification method to (1) be applicable within the scope of this dissertation, (2) resolve the main processes and interactions between the waterborne transport system and the physical environment to make valid assessments, and (3) predict the correct output — i.e., KPI for waterborne transport and impacts on the physical system. The method should:

Scope and applicability

1. be generally applicable,
2. include the system as a whole (be holistic),
3. be applicable in operational (short-term) and strategic (long-term) settings,
4. be modular (flexible),
5. be applicable to open as well as closed systems,
6. be able to perform retrospective (hindcast) and predictive (scenarios) analyses,
7. be available,

Processes

8. be able to include realistic hydrodynamics,
9. be able to include detailed port accessibility policies,
10. be able to schematise waterway layouts in sufficient detail,
11. be able to include vessel properties,
12. be able to encompass vessel-priority rules,
13. be able to schematise berth layouts in detail,
14. be able to include concrete berth-allocation policies,

Output

15. be able to quantify vessel waiting times, and
16. be suitable for predicting hydrodynamic fluxes through lock complexes.

First, for the method's applicability, Criteria 1 and 2 are based on the presented knowledge gap of this dissertation (see Section 1.3); the method should be applicable in different case studies and can capture the nautical traffic system as a whole. Moreover, Criterion 3 signifies that impacts on nautical traffic should be assessed on both short timescales — e.g., operational measures around locks during droughts (see Section 2.2.3) — and long timescales — e.g., the structural impacts of waterway deepening. For this, the quantification method should also be modular (Criterion 4) — i.e., be flexible in the complexity of its assessments — and be applicable in both open and closed systems (Criterion 5). In addition, the method should be able to both perform hindcast studies using data sources as well as scenario studies to assess future impacts and changes to the physical system (Criterion 6). If a method is lacking one of the criteria, it should also be available to the researcher to implement changes and additions (Criterion 7).

Second, for resolving influential processes with the method, Criteria 8–11 are required to accurately model tidal downtime (see Section 2.2.1). In addition, Criteria 12–14 are included to account for terminal congestion (see Section 2.2.2). Lastly, for useful model predictions, Criterion 15 prescribes that the method be able to quantify vessel waiting times, and Criterion 16 is specifically required in closed systems (see Section 2.2.3). The latter can be disregarded in open systems. In the remainder of this chapter, existing quantification methods are discussed and subsequently evaluated based on these criteria.

2.5 Available quantification method components

Identified methods to quantify waterborne transport performance from a nautical perspective can be classified into three categories: analytical tidal accessibility methods (Section 2.5.1), simulation-based methods — ranging from microscopic to mesoscopic and macroscopic (Section 2.5.2), and data-driven methods (Section 2.5.3). This section presents an overview of these methods by highlighting their key features and evaluating their suitability using the assessment criteria in Section 2.4. Moreover, separate subsections are dedicated to quantification methods that predict hydrodynamic data for the above method types (Section 2.5.4), and the applicability of the methods in closed systems (Section 2.5.5). The results of the evaluation are summarised in Table 2.1.

2.5.1 Analytical tidal accessibility methods

Accessibility methods quantify port and waterway performance as the number of navigable tides over the total number of tides, considering the deepest-draughted vessels in the fleet. The tidal windows are calculated based on rule-based algorithms for each waypoint throughout the vessel's route. Two different design approaches are found in the literature: deterministic and probabilistic methods.

Deterministic tidal accessibility methods use static values for the safety components to calculate the UKC. The values are often a minimum gross UKC or a percentage of the vessel's draught. They are generally based on pilots' experiences during the most unfavourable conditions regarding the water levels and the actual draught of the largest vessels. These conditions, however, may only occur infrequently. Due to this conservative design approach, MBLs are frequently over-dimensioned. This may lead to excessively deep port areas, and consequently, less profit for the port.

Probabilistic approaches determine the risk of bottom contact based on the product of the probability, resulting from a certain return period, and the consequences. Accessible time windows are then defined based on periods during which the risk of bottom contact is acceptable over the entire route of the vessel. Three predefined safety criteria exist (Savenije, 1997; Vantorre *et al.*, 2014):

- Single transit bottom touch criterion:
  A criterion that prevents a vessel from touching the bottom, depending on the actual governing hydrometeorological conditions.

- Manoeuvrability criterion:
  A criterion that ensures that the vessel is capable of manoeuvring. It is based on the MM (see Section 2.3).

- Long-term vessel damage criterion:
  A criterion that prevents a certain percentage of maximum minor damage to the waterway in terms of risk (probability times consequences). The probability is derived from a certain acceptable return period. The consequences depend on the expected damage to the vessel, and the resulting damage to the economy and the environment. This results from the type of vessel, the type of channel, the bottom material, and the surrounding ecosystem.

In principle, the long-term vessel damage criterion is governing. However, in the case of favourable conditions, the manoeuvrability criterion overrides the damage criterion.

To apply the probabilistic method, estimates of the vessel motions must be made for different vessel speeds and hydrometeorological conditions. Uncertainty is applied to the bed level, the static draught and the dynamic draught components of the vessel. The uncertainty in the dynamic component is primarily due to uncertainties in the actual and forecasted hydrometeorological conditions. Different methods can be applied to quantify these uncertainties, such as frequent surveys, vessel response prediction based on towing tank experiments and in-situ measurements, and real-time GPS measurements (Parker and Huff, 1998; Vantorre *et al.*, 2008). Since the dynamic response depends on the vessel characteristics (e.g. the shape of the hull, the height of the vessel, loading degree, etc.) the method should be applied to a selection of the deepest-draughted vessels (Bos *et al.*, 2011; Vantorre *et al.*, 2014). The method results in a risk-based dynamic UKC policy (Curtis, 2018). In general, the probabilistic method offers the possibility of applying shallower MBLs.

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However, by focusing on the UKC of individual vessels, current accessibility methods completely ignore the cascading effects between vessels. Moreover, on their own, they cannot model the congestion of locks, terminals and waterways (Criteria 5, 12–14). Therefore, they are not suitable for assessing vessel waiting times and lock hydrodynamics (Criteria 15 and 16). The results of the accessibility methods on the assessment criteria are summarised in Table 2.1.

2.5.2 Simulation-based methods

Microscopic methods

Beyond the approach suggested by PIANC (2014), various simulation approaches are available that resolve vessel waiting times. They range from micro- to macroscopic approaches (Masalaci and Zorba, 2023).

Most methods in the literature are microscopic, meaning they resolve detailed manoeuvres including vessel–vessel and vessel–infrastructure interactions. They tend to focus on waiting times caused by single components of the port network and infrastructure. Examples include heuristic algorithms that minimise congestion-related waiting times at various types of terminals (i.e., de Alvarenga Rosa *et al.* (2017), Venturini *et al.* (2017), and Kramer *et al.* (2019)), and on the waterway (i.e., Jia *et al.* (2019) and B. Zhang *et al.* (2020)). Furthermore, analytical agent-based methods are available that describe vessel motions and behaviour in waterways (i.e., F. Xiao *et al.* (2013), Bellsolà Olba *et al.* (2015), Shu *et al.* (2015), Xin *et al.* (2019), and Durlik *et al.* (2023)), and discrete-event methods that focus on land-based terminal operations (i.e., Cartenì and de Luca (2012), Iannone *et al.* (2016), Wahed *et al.* (2017), Leal (2018), and Neagoe *et al.* (2021)).

Although successful in estimating the delays of individual vessels at specific components of the port, microscopic methods are typically unable to cover the entire port network or the full extent of the traffic, due to computational constraints. In other words, the components of the port cannot be merged to model the port system (Criterion 2). Therefore, these methods cannot be used to assess the impacts on a nautical traffic system at a strategic level (Criteria 3 and 4). Moreover, depending on the method type, they rarely include (realistic) hydrodynamics and detailed accessibility policies (Criteria 8 and 9). The results of microscopic methods on the assessment criteria are summarised in Table 2.1.

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Mesoscopic methods

Mesoscopic methods aim for a compromise where the behaviour of large numbers of individual agents can be simulated, but their behaviour is aggregated to the level of objectively distinguishable events (e.g., mooring, (un)loading, unmooring, anchoring). This allows for a realistic representation of important port processes at scale while keeping computation times at acceptable levels. One of the first mesoscopic simulation models for port operations was developed by J. B. Hansen (1972) and later expanded by Park and Noh (1987). These models focused mainly on land-based terminal operations, typically ignoring hydrodynamic aspects, such as currents and tides. Similar methods were presented by Kondratowicz (1992), Hassan (1993), Demirci (2003), Howard *et al.* (2004), Arango *et al.* (2011), and Ugurlu and Yükseky (2014).

Mesoscopic simulation methods with a stronger focus on nautical traffic schematise the wet infrastructure as a network of nodes and edges, over which vessels navigate and interact. An early model by Clark *et al.* (1983) studied the Suez Canal, excluding port operations. Some later case-specific nautical traffic models that included port operations excluded tidal restrictions, such as the work presented by van de Ruit *et al.* (1995), who studied the Maasvlakte of the PoR, and Yeo *et al.* (2007) who studied the North Harbor of the Port of Busan. Furthermore, the models of Fransen *et al.* (2021) and Nikghadam (2023) focused on waiting times related to the availability of tugs and pilots in the PoR, but these approaches did not account for downtime due to hydrodynamic restrictions.

Mesoscopic methods that quantify waterborne transport performance from a more nautical perspective with a clear focus on congestion and downtime were designed by Groenveld (1983), whose HarbourSim method considered the interactions between calling vessels and the port's infrastructure in detail, including terminal congestion and (tidal) downtime. This method was applied to the Río de la Plata in the work by Frima (2004). Moser *et al.* (2004) created the comparable HarborSym. Other comparable methods were presented by Macquart (2007), Rayo (2013), and Piccoli

(2014). Tang *et al.* (2016) developed a similar method, albeit with a different process interaction-based approach. Furthermore, some case-specific nautical traffic models were constructed by Thiers and Janssens (1998) for the Scheldt Estuary, by Almaz and Altiok (2012) for the Delaware River, and by Scott *et al.* (2016) for the Port of Geraldton. Lastly, various in-house discrete-event methods are known to exist in practice, such as DPCM® (Curtis, 2018) and SiFlow21 (Ayuso *et al.*, 2022), which claim to generically include detailed port congestion and tidal downtime, but no detailed information on these methods is available in the open literature. Recently, the OpenTNSim library has been developed by Delft University of Technology as a mesoscopic agent-based quantification method implementation to model nautical transport networks (van Koningsveld and den Uijl, 2019; Baart *et al.*, 2022). This open-source discrete-event method includes capacity-limited building blocks to model port and waterway infrastructure, and agents that can interact with the waterway network.

While these more generally applicable and multi-temporal mesoscopic methods appear promising — i.e., adhering to Criteria 1–3 — to the researcher's knowledge, none of the methods have simultaneously included all criteria to quantify the cascading waiting times. In general, the methods are often inaccessible and seemingly non-modular, meaning that new modules cannot easily be developed as add-ons (Criterion 4). Moreover, either detailed hydrodynamics and accessibility policies are missing (Criteria 8 and 9), or traffic rules, detailed berth policies, and layouts (Criteria 13 and 14). The method's implementation in the OpenTNSim library was found to be most promising, as it has a modular setup and is accessible to the researcher (Criteria 4 and 7). Although it is not directly applicable to this dissertation's objective, the method can be enhanced, as will be discussed in the next chapter. The generalised results of mesoscopic methods on the assessment criteria are summarised in Table 2.1.

Macroscopic methods

In contrast to the number of microscopic methods, only a few macroscopic methods are presented in the literature. These methods focus on traffic flows rather than the behaviour of individual vessels. Koldborg Jensen *et al.* (2013) used a mathematical model to calculate the efficiency of a waterway, while Tasseda and Shoji (2018) developed a model to unravel the vessel traffic in Tokyo Bay. Queuing theory is another type of macroscopic method (Dragović *et al.*, 2012; Navarro *et al.*, 2015).

Macroscopic methods, while good at scale, lack resolution to resolve the detailed causes of waiting times, particularly in closed systems (Criteria 4 and 5). Moreover, there is a general lack in the availability of these methods (Criterion 7). None of the methods mentioned in the literature includes realistic hydrodynamics, detailed accessibility policies, and berth availability information, which are required to resolve the processes of tidal downtime and berth congestion (Criteria 8–14). The methods are therefore unable to fully quantify vessel waiting times and lock hydrodynamics (Criteria 15–16). The results of macroscopic methods on the assessment criteria are included in Table 2.1.

2.5.3 Data-driven methods

The use of Automatic Identification System (AIS) data to assess waiting times in port and waterway systems is a relatively new trend. Franzkeit *et al.* (2020) and Ma *et al.* (2023) focused on vessel waiting times in anchorage areas, Martiničič *et al.* (2020) analysed arrival and turnaround times of vessels in the Port of Piraeus, Jafari Kang *et al.* (2022) studied congestion in the Port of Houston, and Steenari *et al.* (2022) investigated the performance of berths in the Port of Brest. A stand-alone AIS data analysis, however, is typically insufficient to unravel the detailed causes of vessel waiting times. This is due to the complex dependencies that exist between vessels and port infrastructure that cannot be deduced in full from AIS data alone without additional data and/or simulations (van der Werff *et al.*, 2024a; van der Werff *et al.*, in prep.). Therefore, the methods do not apply to scenario studies (Criterion 6) and are hardly able to resolve underlying processes of tidal downtime and berth congestion (Criteria 9–10, 12–14). However, they can be used to quantify waiting times and lock hydrodynamics based on vessel behaviour solely (Criteria 15 and 16). Therefore, data-driven methods are useful in calibration and validation studies of quantification methods.

2.5.4 Hydrodynamic modelling methods suitable for nautical traffic modelling

Based on the previous section, it was found that realistic hydrodynamics are rarely included in nautical traffic performance methods. Therefore, this section provides details on how quantification methods for nautical traffic can be enhanced by establishing a coupling with hydrodynamic modelling methods. Estuarine hydrodynamics are primarily dependent on tides, river discharge, storm surges, and estuary geometry (Hoitink and Jay, 2016). The water levels and current velocities vary temporally and spatially over the width and depth. These variations affect nautical traffic through accessibility policies set by the port authority (see Section 2.2). These rules depend on the level of hydrodynamic information that the authorities have, the port and estuary type, and the experiences of pilots. For example, in the PoR, accessibility rules are based on predicted water level and depth-dependent current velocity output based on a detailed numerical model (Kranenburg *et al.*, 2015). In contrast, the pilots of PoA use real-time current velocity and wave height measurements. In general, port and waterway systems with long channels require spatial information (see Section 2.2.1), while short channels can suffice with a single data point. Moreover, ports with strong depth-varying (cross–)currents generally require depth-dependent current velocity data.

The presented state-of-the-art quantification methods rarely include such detailed hydrodynamic data. However, vessel manoeuvrability simulators (Donatini *et al.*, 2019) and accessibility tools (Bos *et al.*, 2011; Vantorre *et al.*, 2014) are the most common to incorporate such input. Simulators typically use numerical methods, whereas accessibility tools generally use data-driven approaches.

Numerical methods are generally required to predict the hydrodynamics of an entire system. There are many types of numerical methods that can distinguish methods based on their temporal and spatial discretisation. For time discretisation, numerical methods typically use a constant time step of several seconds to resolve tidally varying water levels and current velocities. In contrast, tidally-averaged methods, such as described by Talke *et al.* (2009), focus on the transport of matter and do not resolve these intratidal hydrodynamics. The latter types of methods are not unsuitable for modelling tidal downtime.

For spatial discretisation, numerical methods can use different vertical and horizontal grid types for specific purposes (Bomers *et al.*, 2019; Wise *et al.*, 2022). The following types are available: 1D (depth- and width-averaged or horizontally-averaged), 2DV (width-averaged), 2DH (depth-averaged) and 3D (Glock *et al.*, 2019). For instance, Sirviente *et al.* (2023) applied a depth- and width-averaged 1D model in the Guadalquivir River Estuary to estimate thalweg-varying water levels and current velocities. A 2DV approach is used by Dijkstra *et al.* (2017) and Biemond *et al.* (2024a) which can estimate water levels, current velocities and saltwater intrusion, at the expense of not having complex geometries, such as harbour basins. In estuaries with a more complex geometry, a 3D hydrodynamic model is preferred. For example, L. Zhao *et al.* (2022) deployed such a model to simulate morpho-hydrodynamics in the Yangtze Estuary, including salinity. More details on hydrodynamic modelling in estuaries can be found in Fringer *et al.* (2019).

In addition to numerical methods, data-driven methods can estimate water levels and current velocities. A well-known example is Fourier analysis (Parker, 2007; Raimundo and Costa, 2021), which can generate purely astronomical tidal water levels and currents for long timescales. Moreover, Guerra-Chanis *et al.* (2022) and Wullems *et al.* (2024) developed a data-driven saltwater intrusion model using machine learning. A downside of these data-driven approaches is that they cannot quantify the effects of changes to the estuarine system on the hydrodynamics. They are therefore not suitable to assess natural or man-made changes. Moreover, these methods rely on long time series of data, which are sometimes unavailable. Furthermore, they often do not capture the required spatial scale.

The ultimate choice of method depends on the research requirements and the accessibility policy. In principle, to implement exact accessibility rules in a quantitative nautical traffic modelling method, the same data source should be used. Data-driven methods are excellent in hindcast studies, while in scenario studies — e.g., a waterway to be deepened — the data should be obtained using a validated numerical model. If a port authority is using such a model, preferably this model should be used. Otherwise, a model should be set up, for which data and data-driven methods can be used for calibration and validation (Williams and Esteves, 2017). Regarding water levels, a 1D modelling method can be applied if the channel geometry is simple, otherwise a 2DH is preferred. Based on the findings of Menten *et al.* (2023), who compared a 2DH with a 3D hydrodynamic model in the Minho River Estuary, depth resolution may be required to better estimate current velocities. They found that depth-averaged methods can be used to estimate saltwater intrusion lengths in well-mixed estuaries, but can lead to significant discrepancies with observations when relevant stratification is present. This is because of the lack of accurate depth-dependent current velocities. Therefore, for stratified estuaries, depth-resolving numerical modelling methods perform better (Cai *et al.*, 2022) and are hence required — i.e., a 2DV (for simple estuary geometry) or a 3D modelling method (for complex estuary geometry). In addition, a depth-resolving method may be required if the port authorities are using such data to determine the cross-current velocities experienced by vessels. Note that depth-averaged methods can also determine this by assuming the logarithmic law of the wall. Ultimately, the choice of hydrodynamic modelling method depends on a trade-off between accuracy and runtime; complex methods are computationally more expensive.

2.5.5 Quantification methods for closed systems

Up until this section, only the applicability of quantification methods for open systems has been discussed. For decision-making in a closed system, a quantification method is required to include local navigation lock operations (Criterion 5). This method should simultaneously assess the KPI for waterborne transport (i.e., vessel waiting times) and the effects on freshwater losses and saltwater intrusion fluxes through the locks (Criteria 15 and 16).

In the literature, various microscopic locking methods can be found. They focus on the local nautical traffic dynamics. Rijkswaterstaat (2000) developed SIVAK-package to model nautical traffic around infrastructural objects, including elaborate modules for locks. It has, for example, been applied by L. Chen *et al.* (2013) to model lock delays to determine the capacity of the inland waterway network in North Zhejiang, and by ten Hove and Bilinska (2015) to model the capacity of a sea lock at Terneuzen. Lock scheduling was performed by van Adrichem (2019), whose results were compared to those predicted by SIVAK. Moreover, Verstichel *et al.* (2014) focused on the lock scheduling problem using a heuristic model, and Y. Zhang *et al.* (2023) with a mathematical model for the lock complex at the Three Gorges Dam. Bačkalić and Bukurov (2011) developed a different microscopic simulation method to assess the locking process of vessels in parallel lock chambers. A downside of these microscopic methods is that they are typically unable to be implemented in a mesoscopic traffic model that covers the entire waterway network, due to computational constraints (Criteria 2–4).

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Few alternative methods are available in the literature. Regarding macroscopic methods, Dai and Schonfeld (1998) applied the queuing theory to determine vessel delays. Smith *et al.* (2009) and Wilson *et al.* (2011) performed a cost analysis of lock delays in the Mississippi inland waterway network using rule-based programming, and Liao (2018) developed an analytical model. Moreover, a data-driven method that uses probabilistic variance analysis was employed by Asamer and Prandtstetter (2015) on lock passage data to estimate vessel delays at locks. Mesoscopic nautical traffic modelling methods for closed systems are also scarce. Caris *et al.* (2010) and Macharis *et al.* (2011) developed a discrete-event model for barge traffic over an inland waterway network, called SIMBA. The OpenTNSim library (see Section 2.5.2 and van Koningsveld and den Uijl (2019) and Baart *et al.* (2022)) can also be used to model nautical traffic in closed systems, as it includes a simple lock module.

However, none of the aforementioned methods for closed systems include hydrodynamics (Criterion 8). While the effect of different lock designs and operations on vessel delays can be assessed (Criterion 15), the hydrodynamic exchange fluxes cannot be quantified, as the methods were found not to resolve the door-open and levelling phases that lead to these fluxes (Criterion 16).

To include these fluxes, separate hydrodynamic modelling methods can be found in the literature that estimate the hydrodynamics around locks. On the scale of the lock complex, Nielsen (2011) used computational fluid dynamics (CFD) to model saltwater intrusion through navigation locks in detail for Lake Washington. CFD is widely applied for this purpose — e.g., Oldeman *et al.* (2020). A more simplified exchange volume module is presented by van der Ven *et al.* (2015), called WANDA-locks. However, these methods are computationally expensive and cannot be included in system-scale and strategic settings (Criteria 2 and 3).

At a system scale, Parchure *et al.* (2000) used a volume balance to estimate saltwater intrusion in Lake Gatún. Moreover, numerical methods have been adopted that schematise saltwater intrusion and freshwater losses through locks using exchange coefficients, such as Augustijn *et al.* (2011) and Rinehimer *et al.* (2019).

The most complete model found is the one by Wijsman (2013), who combined a numerical hydrodynamic modelling method with salinity boundary conditions based on a detailed semi-empirical model called SWINLOCKS — although the source code for this method is not openly available. Recently, Weiler *et al.* (2019) and Weiler and Bijlsma (2023) developed a similar semi-empirical method, called the Zeesluisformulering, which can quickly estimate the saltwater intrusion fluxes and freshwater losses through locks. This method has been applied by the Scheldecommissie (2023) to model saltwater intrusion in Canal Ghent-Terneuzen. However, these hydrodynamic modelling methods do not include an explicit coupling with traffic that uses the lock. While changes in the saltwater intrusion fluxes and freshwater losses can be quantified, they cannot assess the effects on vessel delays (Criterion 15).

In conclusion, to the researcher's knowledge, no method directly couples nautical traffic with lock hydrodynamics. The only method that simultaneously incorporates both lock hydrodynamics and traffic across an entire transport network is the mesoscopic nautical traffic modelling quantification method implemented through the OpenTNSim library. This is as highlighted in Table 2.1.

Table 2.1: Overview of the quantification method types and their criteria-based evaluation (details in the text)*

	Criteria															
	Scope and Applicability							Processes							Output	
Method type	1. Genericity	2. Holisticity	3. Multi-temporality	4. Modularity	5. Closed systems	6. Available	7. Hindcasts and predictions	8. Realistic hydrodynamics	9. Accessibility policy	10. Waterway layout	11. Vessel properties	12. Traffic rules	13. Terminals layout	14. Berth-allocation policies	15. Vessel waiting times	16. Lock hydrodynamics
Analytical methods	+	~	+	~	−	+	+	+	+	+	~	−	−	−	~	−
Microscopic methods	+	−	−	−	+	+	+	−	~	+	+	+	+	+	+	+
Mesoscopic methods	+	+	+	~	−	~	+	~	~	+	+	~	~	~	+	−
OpenTNSim library	+	+	+	+	~	+	+	~	~	+	+	~	~	~	+	~
Macroscopic methods	+	+	+	−	−	−	+	−	−	~	~	−	−	−	~	−
Data-driven methods	+	+	+	+	+	+	−	+	+	+	+	~	+	~	+	−

*Scores: good (+), moderate (~), poor (−)

2.6 Conclusion

This chapter presents a literature review aimed at evaluating the suitability of existing methods to quantify the performance of water transport based on the physical state of the system. As such it addresses sub-question 1 (SQ 1): *How effectively can existing methods assess the waterborne transport performance by quantifying its underlying interactions with the physical system?*

In conclusion, mesoscopic simulation-based nautical traffic modelling methods are the most suitable method for quantifying the impact on waterborne transport performance, as they cannot resolve the system-scale interactions between waterborne transport and the physical environment. In open estuaries, these interactions are governed by cascading effects between tidal downtime and congestion, whereas in closed systems lock operations are dominant. To assess this, the method should be able to quantify vessel waiting times as the most important KPI for the nautical perspective of waterborne transport. The mesoscopic simulation-based methods have the advantage over other method types due to their modularity — i.e., they are able to adaptively simulate both small-to-large-scale systems with sufficient local detail, for short-to-long timescales — while being predictive. However, none of the existing and openly available mesoscopic simulation-based methods prove to be directly suitable to assess the impacts on nautical traffic, as they do not simultaneously account for detailed tidal accessibility, berth allocation policies, realistic hydrodynamics (e.g., water levels, current velocities, and lock exchange fluxes), traffic rules, and terminal layouts. In addition, nearly all mesoscopic simulation-based methods fail to resolve lock operations in closed systems. Therefore, they are unable to quantify freshwater loss and/or salt intrusion fluxes.

The mesoscopic simulation-based nautical traffic modelling method implemented through the OpenTNSim library is, despite its specific shortcomings, the most promising method to use as a platform for further development. The main advantage of this discrete-event method is that it has building blocks to simulate the interactions between nautical traffic and the physical environment in both open and closed systems (Criteria 4–6), is accessible to the researcher (Criterion 7), and can resolve lock hydrodynamics (Criterion 16). The next chapter discusses suggested modifications to this method to achieve the desired capability for both open and closed systems.

3

A method to assess waterborne transport performance in estuaries

Perfection is achieved not when there is nothing more to add, but when there is nothing left to take away.

Antoine Marie Jean-Baptiste Roger de Saint-Exupéry

In Chapter 2, one can observe that economically viable port and waterway systems require their KPI of vessel waiting times to be limited. Therefore, cascading effects between tidal downtime and congestion that emerge from interactions between the port infrastructure, fleet, and physical system, should be limited. However, no openly available quantification method simultaneously accounts for these processes, meaning that vessel waiting times cannot be fully quantified. The quantitative mesoscopic nautical traffic modelling method implemented through the OpenTNSim library is found to be able to overcome these shortcomings, but still lacks the underlying algorithms for this. This leads to the question (SQ 2): **How can the most suitable quantification method be enhanced to more extensively include the interactions between waterborne transport and the physical system?** To answer this question, this chapter presents new algorithms that account for these interactions to model vessel waiting times in open and closed systems accurately. These are added to OpenTNSim as a Seaport and Locking module. Thus, a coupling with existing hydrodynamic modelling methods is made. Implementation of this method shows that the algorithms can successfully simulate cascading waiting times due to limited port accessibility caused by a shallow MBL in open systems. Moreover, in closed systems, the established quantification method is able to estimate the impact of operational countermeasures aimed at limiting freshwater losses and saltwater intrusion on vessel delays. Although further refinement of the method is possible, the proposed modifications provide an important first step in quantifying the impact of the physical system changes on waterborne transport, and vice versa.

This chapter is based on two conference papers, respectively published as:

Bakker, F.P. & van Koningsveld, M. (2023). *Optimizing bed levels in ports based on port accessibility.* In: Proceedings of 37th International Conference on Coastal Engineering doi: https://doi.org/10.9753/icce.v37.papers.62;

Bakker, F.P. & van Koningsveld, M. (2024). *Tool to evaluate countermeasures at locks to limit freshwater losses and saltwater intrusion while minimizing waiting times for shipping.* In: Proceedings of 35th PIANC World Congress url: https://bit.ly/3MLqrHw

The underlying software is published as: Bakker, F.P. & Baart, F. & Van Koningsveld, M. (2024). *Version v1.4.0-paper.3.* Zenodo. doi: https://doi.org/10.5281/zenodo.11489436

3.1 OpenTNSim: a library for discrete event-based nautical traffic modelling

To include vessel interactions and better quantify nautical accessibility, the OpenTNSim library, developed by the Delft University of Technology (van Koningsveld and den Uijl, 2019) and further enhanced by Baart *et al.* (2022), provides a suitable method. OpenTNSim is an open-source discrete-event simulation library in Python[1] that can be used in a generic manner to investigate the mesoscopic behaviour of port and waterway networks. This mesoscopic level is of particular interest for problems that simultaneously require a large study area and more detailed engineering methods to quantify specific aspects of the network or of the agents using it (van Koningsveld *et al.*, 2023). Hence, it is very suitable to investigate the effect of the chosen design MBLs in a port. The remainder of this section describes the quantification method in more detail.

OpenTNSim is built upon the discrete-event simulation package of SimPy[2]. It works according to the following principles:

1. The behaviour of the active components (vessels) is modelled with processes:
   The processes are defined by Python's generator functions. These functions generate time steps in the method — i.e., when an event starts or stops. An example is a "timeout" generator with a variable, pre-calculated step time. This can be used to simulate a loading, sailing, and waiting events of vessel, for example.

2. All processes exist within an environment:
   The environment organises all processes and coordinates them in the same timeframe. For example, two vessels with different loading times can be loaded simultaneously, while keeping track of their respective start and stop times.

3. The processes interact with the environment and with each other through events:
   Events are process functions that can interact with other events, and thus with other components. For instance, SimPy can model a vessel that is waiting for another vessel to finish loading (see next section).

3

Simpy has shared resources with a limited capacity that can be triggered by events. These resources can represent port infrastructure. They are classified into three categories:

1. Resources:
   Resources can be used by a limited number of processes at the same time, which corresponds to their capacity. When all slots are taken, new process requests are queued. Once a user request is released, a pending request will be granted. For example, terminals with jetties (e.g., liquid bulk terminals), turning basins and anchorage areas can be modelled as resources, as they have a finite integer number of capacity. When a terminal with a single jetty is occupied, no other vessel may use the terminal. A request can have a priority and can also be pre-emptive, meaning that it can override a previously granted request.

2. Containers:
   Containers have a finite capacity for matter that can either be continuous or discrete. They support requests to place or remove matter into/from the container. If there is insufficient capacity left to place new matter or if there is not enough matter left to be removed, a new request will be queued. This concept can be applied to model infrastructural components with a given length, such as terminals with quays (e.g., dry bulk and container terminals), vessel hull capacity and terminal storage capacity. For example, a quay with a length of 300 m that is occupied by a vessel of 200 m can only be claimed by another vessel with a length of 100 m or less.

3. Stores:
   Stores enable the production and consumption of Python objects, rather than a quantity of matter as in the case of containers. This allows for the modeling of a collection of different resources — e.g., a number of jetties with distinct dimensions for different vessel sizes. A

[1] https://www.python.org/
[2] https://pypi.org/project/simpy/

vessel can then be assigned a jetty that fits its dimensions or instructed to wait for the availability of such a jetty.

OpenTNSim's Core module models vessels as agents that move through time and space (see Figure 3.1), for which it discretises both time and space. In time, the provided quantification method uses a discrete event system specification to discretise time. Rather than using constant time steps, the method uses variable time steps that are defined by the events themselves. As a result, output is generated whenever events start or stop. In space, OpenTNSim relies on the open-source NetworkX package to model the port network of waterways (see Figure 3.1). This package can construct a transport graph and select routes based on criteria. Such a graph consists of nodes and edges to which infrastructure, schematised by the shared resources of SimPy, can be assigned. Geographical information can be provided to the graph through the Geospatial Data Abstraction (GDAL) Library[3], which calculates distances between the nodes and the positions along an edge. The time and space discretisation are further discussed in more detail in the following section (see Figure 3.2).

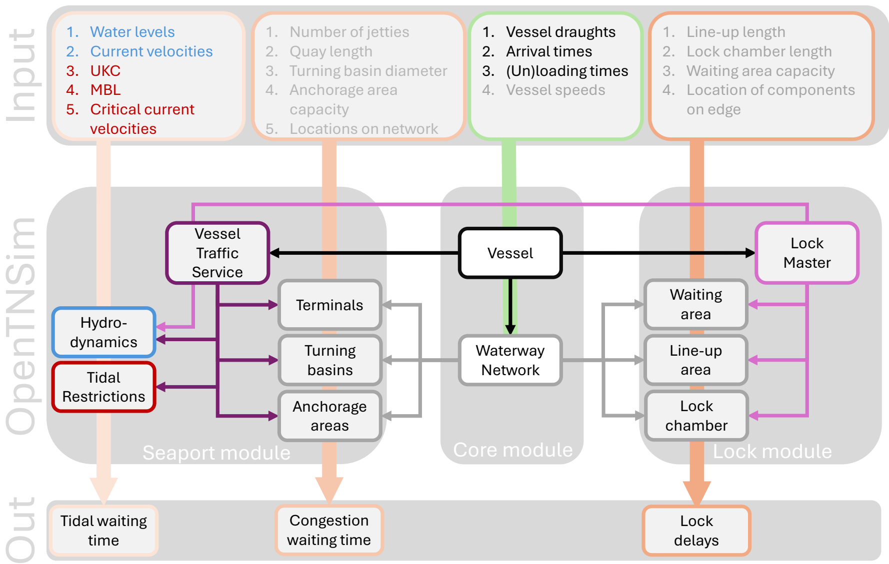

Figure 3.1: Schematic overview of the coupling (arrow) of different mixins (frames) in the Seaport and Locking modules to the core module of OpenTNSim, including the required input and expected output (more details in the text).

Specific information can be assigned to each vessel, such as its route, its vessel characteristics (e.g. draught), and vessel speed over the edges of the network. During the simulation, the vessel's time and location are continuously tracked.

OpenTNSim offers a library of standardised object-oriented classes, called 'mixins', that can be combined to create vessels or infrastructure components with user-specified properties and behaviour. Adding the 'Identifiable' mixin to an agent, for example, allows the user to give that agent a name and/or a Universal Unique Identifier (UUID)[4]. Adding the 'Movable' mixin enables an agent to move at a predefined speed. The 'Routeable' mixin, which implies 'Movable', allows an agent to move over a graph following a specified route with an origin, intermediate waypoints, and a destination. The 'VesselProperties' mixin allows the user to specify vessel properties, such

[3] https://pypi.org/project/GDAL/
[4] https://pypi.org/project/uuid/

3

as length (L), beam (B), draught (T), and payload. The 'Log' mixin ensures that key information is logged for later inspection.

The OpenTNSim library is designed to allow system components to be easily constructed by adding multiple mixins. New mixins can be developed and added to its library. In this dissertation, a Seaport module and Locking module are added to the library, which are published as software in Bakker *et al.* (2024).

3.1.1 The seaport module

To model the behaviour of seagoing vessels in port and waterway systems, a Seaport module was developed by reusing existing mixins and adding new ones. The module's functioning is illustrated in Figure 3.1.

Various new 'PortInfrastructure' mixins were developed that schematise the port and waterway infrastructure, consisting of anchorage areas, turning circles, and terminals with berths, i.e., jetties and quays. These mixins can be named by adding the 'Identifiable' mixin. Moreover, they rely on the SimPy-defined Shared Resources (see previous section). Some infrastructure can only operate one vessel at a time – e.g. turning circles and jetties — while others can accommodate multiple vessels — e.g. anchorage areas. These are modelled using a Resource object. The user can specify how many vessels can use that object at the same time by adding a 'HasResource' mixin. A quay has a certain length that can be schematised with a Container-resource object. A terminal combines multiple berths by using the FilterStore object.

Moreover, a 'VesselTrafficService' mixin was developed. When this is added to an object, it handles requests for information from a port authority, such as the availability of a berth and the tidal windows. To calculate the availability of a tidal window, the mixins use information that is added to the transport network graph, such as the applicable MBL and UKC policies per network edge, and the hydrometeorological conditions predicted by hydrodynamic modelling methods. The 'VesselTrafficService' mixin communicates berth availability in advance, meaning that a vessel can already enter the port and proceed to its assigned berth when the preceding vessel is scheduled to leave the berth in time. If the capacity has been reached — i.e., a jetty that can handle one vessel at a time and is already occupied — then the next vessel that needs to use that jetty has to wait until it becomes available. Waiting is typically performed in one of the port's anchorage areas.

The behaviour of the vessels is modelled through events that utilise both vessel and network information. The following events are modelled, as shown in the example of Figure 3.2:

- Sailing (*part of existing OpenTNSim library*):
  Sailing is modelled using a timeout event assigned to a vessel to pass an edge. Since it is assumed that the speed of the vessel over the specific edge is known, the sailing time can be calculated based on the distances between the nodes. After the event, the vessel's location information is updated to match the location of the end node of the edge.

- Requesting terminal access:
  When a vessel arrives near the anchorage area, it requests the resource that represents the terminal. When the terminal is occupied, SimPy can determine the waiting time of the vessel — the difference between the start time of the waiting event and the time when the terminal's user request is released, minus the estimated sailing time. Once this event is completed, the vessel can leave the anchorage area. As mentioned above, a request can be pre-emptive, allowing it to take priority over an earlier granted request.

- Requesting port entry:
  The tidal window calculation is based on the deterministic approach of PIANC (2014) for calculating the minimum required available water depth, see Section 2.3. If a tide-bound vessel arrives outside of a tidal window, the event assigns the vessel a waiting time, so that its new entry time equals the starting time of the next forecasted tidal window. The event must be completed before the vessel can leave the anchorage area.

- Turning, berthing and loading:
  By knowing the size and loading degree of the vessel, the time required for a vessel to turn in the turning basin during its return trip, the berthing time, and the loading time can be determined. These are modelled by a timeout event required to pass these infrastructures.

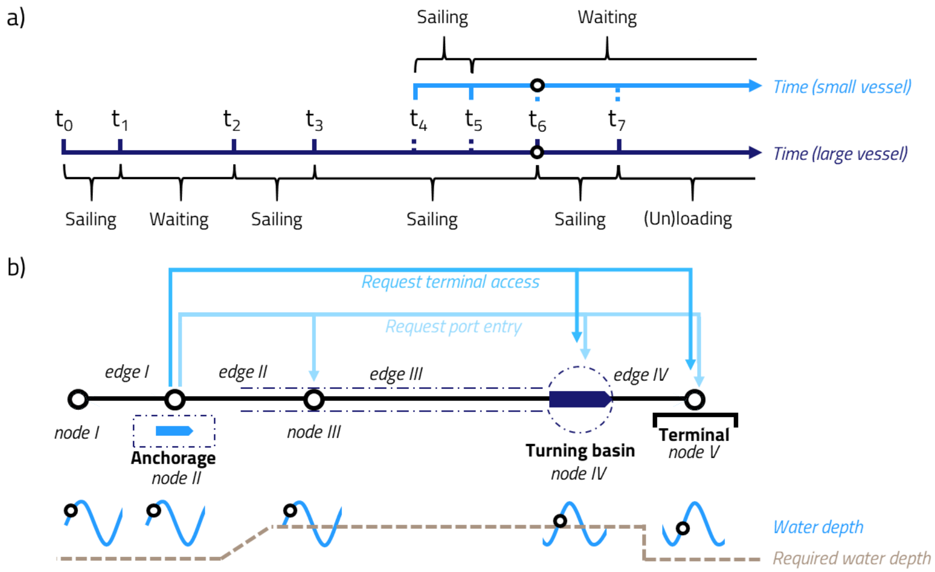

Figure 3.2: Overview of the time (a) and spatial (b) discretisation in OpenTNSim, for the Seaport module (more details are provided in the text).

The above events determine the time steps in OpenTNSim (see Figure 3.2a). These events are triggered by agents (vessels) that interact with a network. Figure 3.2b presents a typical network consisting of an anchorage area (at node II), a turning basin (at node IV), and a terminal (at node V). The figure shows the spatial outcome of a specific time step, t_6, in the timeline of a discrete event simulation of two vessels requesting the same terminal with a unit capacity. The large vessel arrived earlier, sailed to node II ($t_0 \rightarrow t_1$), and, here, made a request for the terminal, which was granted as it was available. However, as it requested to enter the port, it was instructed by the Vessel Traffic Service to wait in the anchorage area for a tidal window, as the required water depths were insufficient at that time ($t_1 \rightarrow t_2$). At flood tide (t_2), the large vessel receives permission to enter, subsequently leaves the anchorage area, and proceeds to the terminal ($t_2 \rightarrow t_7$). During this transit, a smaller vessel arrives at the port at t_4, and sails to the anchorage area ($t_4 \rightarrow t_5$), where it requests access to the terminal. This vessel is not subjected to the tidal windows but must wait until the terminal becomes available (from t_5 onwards). After t_6, the large vessel sails to the terminal ($t_6 \rightarrow t_7$), unloads (from t_7 onwards), sails out, turns, and leaves the port. Hereafter, the smaller vessel proceeds to the terminal and follows the same steps as the large vessel.

In conclusion, the Seaport module is able to model tidal downtime and congestion. This will be further tested in Section 3.2.

3.1.2 The locking module

The existing lock module in OpenTNSim has been improved to simulate vessel behaviour around locks in more detail (see Figure 3.1). It spatially discretises locks into five components (see Figure 3.3): an outer and inner waiting area (I) in each harbour used by vessels to wait if the lock is unavailable, a line-up area (II) after the waiting area to prepare vessels for entry into the lock chamber, and the lock chamber (III), where the vessels are locked. The method discretises a lock passage in time in eleven phases (see Figure 3.3): the arrival of the vessel within a certain time range from the lock (0), sailing towards the waiting area (0→1), waiting in the waiting area (if required, 1), sailing towards the start of the line-up area (1→2), positioning in the line-up area (2→3), waiting in the line-up area (if required, 3), sailing to the end of the line-up area (3→4), sailing to the first encountered lock doors (4→5), positioning in the lock chamber (5→6), waiting for other vessels (if required, 6), levelling of the lock chamber (6), sailing to the second encountered lock doors (6→7), sailing to the end of the opposite line-up area (7→8), sailing to the start of the opposite line-up area (8→9), and sailing to the opposite waiting area (9→10), before leaving the lock complex.

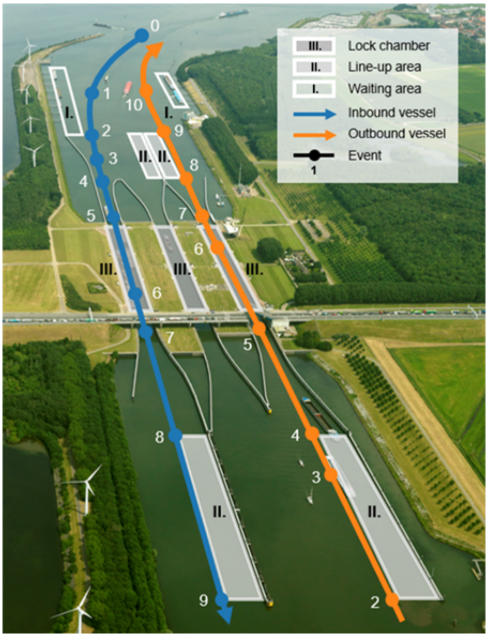

Figure 3.3: The Volkerak lock complex with highlighted infrastructural elements that are critical for modelling the vessel behaviour (logistics) during lock passages. Critical elements and events are numbered, the background image was retrieved from https://beeldbank.rws.nl, Rijkswaterstaat).

The lock module utilises the concepts of SimPy's Shared Resources, namely Resource objects and Container objects (see Section 3.1), to respectively schematise the availability of lock doors (one vessel at a time leaving/entering a navigation lock) and available length of the lock chamber and line-up area (with a variable, finite number of vessels that can fit, depending on their total length). By carefully tracking the vessels' requests for the lock doors (to enter or leave the lock), and the lock chamber (to determine if the lock is fully occupied or available for the next vessel), lock operations can be modelled and the corresponding vessel behaviour can be resolved. Hence, the waiting times of vessels can be estimated, along with many other performance indicators of both the vessels and the lock. Prioritisation rules, operational hours, and clustering regulations can be incorporated into a model. Additionally, levelling times can be based on empirical relations that depend on the water level difference over the lock. These water levels can be requested through the 'VesselTrafficService' mixin in the Seaport module.

As the lock operations cause saltwater intrusion and freshwater losses, the Locking module is designed to be compatible with a fast semi-empirical hydrodynamic modelling method of a lock. Due to the similarity in the discretisation, the semi-empirical Zeesluisformulering (Weiler *et al.*, 2019) was chosen for this. This semi-empirical method algorithmically describes how saltwater is exchanged by lock operations, which helps to quantify the impact of mitigating measures. Although the formulation is simplified with many assumptions that are often violated in reality, it can rapidly estimate the order of magnitude of saltwater intrusion. Since traffic is not directly included in the Zeesluisformulering, but rather aggregated by averaging operational parameters and by using calibration factors based on observations, it was integrated into OpenTNSim. The Zeesluisformulering discretises the lock operation in four phases: two door-open phases at both harbours, separated by (two) levelling phases. For each phase, it calculates the water discharges in and out of the lock, including the salt fluxes, which are estimated based on assumed homogeneous salt concentrations in the lock and both harbours. Although these events occur simultaneously, the Zeesluisformulering models these processes separately.

First, the preceding vessel(s), if any, will exit the lock. Then, the exchange flow between the fresh- and saltwater will start (starting when the doors are half open). Last, the exchange flow will stop (when the doors are half closed) and the next vessel(s), if any, will sail into the lock. Each event results in fresh- and/or saltwater fluxes between the lock and the harbour. The speed of the exchange current is assumed to be constant and dependent on the water depth and salinity difference between the lock and the harbour. Additional flushing of freshwater can be applied during the door-open phase, which results in a reduction factor for the exchange volume of saltwater, as well as an additional freshwater flux to the lock. Moreover, additional reduction factors to the exchange current speed are applied if bubble screens are used. In principle, the lock chamber will be gradually exchanged, with the current advecting toward the closed lock door, reflecting there, and fully advecting to the opened lock door (a distance equivalent to twice the lock length). The fraction of exchanged water follows a relation based on the hyperbolic tangent, which closely approximates the natural behaviour of the exchange flow; the exchange current speed gradually decreases as the density difference between the lock and harbour further decreases. During the levelling phase, either fresh- or saltwater is used, depending on the water levels of the opposing harbours. More details on the formulation can be found in the reports by Deltares (Weiler *et al.*, 2019).

The lock module in OpenTNSim and the Zeesluisformulering are fully complementary as they explicitly model the same locking phases. Therefore, OpenTNSim, which can incorporate the ambient hydro-dynamics (i.e., water levels and salt concentrations) can be included, provides the necessary information to the Zeesluisformulering such that it can estimate the exchange fluxes for each lock operation individually. This includes the exact door-open times, the total volume of vessels sailing in/out of the lock, the water depths, the salt concentrations, and the levelling volumes. The levelling volumes and times can be based on the discharge curves of various filling and emptying systems, as well as the governing water levels. The coupled method is further tested in the next section.

3.2 Method testing

To test the new algorithms, simplified cases have been designed for both open and closed systems, which are presented in this section, respectively.

3.2.1 Open system

OpenTNSim is used to simulate the nautical traffic behaviour at a liquid bulk terminal in the PoR. This terminal is located in the 3e Petroleumhaven (3e PET), located along the main waterway, the NWW (see Figure 3.4). The implementation of the quantification method requires the following input:

- Network:
  The graph of nodes and edges follows the entrance channel from the anchorage area to the liquid bulk terminal. It is derived from Rijkswaterstaat's Fairway Information System (FIS[5]), which includes geographical data, along with other information.

- Infrastructure:
  The following infrastructure is added to the graph: an anchorage area (located on an offshore node at 25 km from the start of the entrance channel), a turning basin on a node in the harbour basin (situated on a node in the harbour basin 150 km from the start of the entrance

[5] https://www.rijkswaterstaat.nl/water/scheepvaart/scheepvaartverkeersbegeleiding/river-information-services/fairway-information-service

channel), and a terminal (at the final edge of the route at 152 km from the entrance channel). There is a unit capacity at both the turning basin and terminal, while the capacity of the anchorage area is unlimited.

- UKC and hydrodynamic data:
  The nodes are enriched with predefined MBL designs, as well as UKC and FWA policies. Furthermore, water levels and current velocities are assigned to the nodes, obtained from a numerical model. The Nieuwe Waterweg has a MBL of 16.4 m. The gross UKC policy prescribes a clearance of 10% of the vessel draught relative to the MBL. Furthermore, the FWA initially equals 1.0% of the vessel's draught, which increases to 2.5% after a distance of approximately 14 km from the heads of the breakwaters (de Jong, 2020). The entrance channel and the harbour basin do not impose draught limitations. At the entrance of the harbour basin, there is a horizontal tidal window for all vessels as entry is prohibited when the current velocity exceeds 1 kn.

- Vessels:
  Two Long Range (LR) tanker vessels are modelled: an LR1 and a larger LR2 vessel, with static draughts of 12.2 and 15.0 m, respectively. Both vessels have a speed of 9 kn and unloading times of 3.8 and 4.7 days, respectively, as estimated by de Jong (2020) based on AIS data. The LR2 vessel is subject to a vertical tidal window, while the LR1 vessel has no water depth limitations.

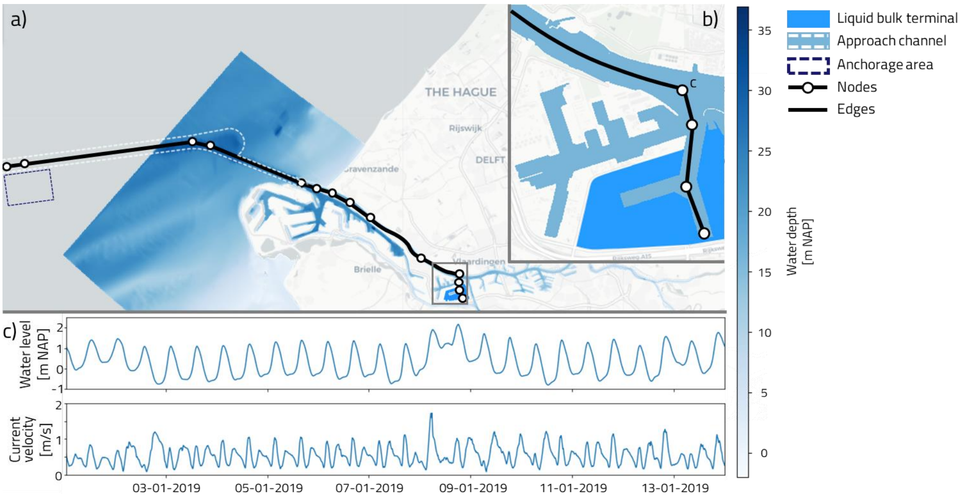

Figure 3.4: Overview of the case study of the liquid bulk terminal in the Port of Rotterdam (a), with a close-up at the harbour basin of the liquid bulk terminal (b), including the water level and current velocity data (c) at the entrance of the harbour basin (node c).

A situation is considered where the LR2 vessel arrives on the first day of the simulation, and the LR1 vessel arrives on the fifth day. The vessel waiting times are calculated as KPI for waterborne transport. Two scenarios are run:

1. No congestion due to tidal windows:
   A situation in which the LR2 vessel is not subject to a tidal window; it arrives at a time that falls within a tidal window, and finishes (un)loading at a time that also falls within a tidal window.

2. Congestion due to tidal windows:
   A situation in which the arrival times of both vessels (LR1 and LR2) are delayed by the same amount, causing the arrival time of the LR2 vessel to fall outside of a tidal window. This results in the preferred departure time also falling outside of a tidal window.

3.2.2 Closed system

A simple case study is set up to demonstrate the applicability of the nautical traffic simulation modelling library OpenTNSim in closed systems. The simulated scenarios include a lock complex for seagoing vessels with a single chamber. The chamber has a length of 500 m, a width of 40 m, and a depth of 11.5 m. The outer harbour (seaside) experiences a sinusoidal tidal wave with an amplitude of 1 m and a salt concentration of 25 kg m^{-3}. The inner harbour maintains a constant water level of 0 m with no salinity. Vessels are generated on both sides of the lock, each with a length of 200 m, a beam of 35 m, and a draught of 10 m. They arrive according to a uniform arrival distribution with an average of two vessels per hour (intensity/capacity = 0.25). To explore the effect of the clustering of vessels on saltwater intrusion and vessel delays, various clustering rules are applied. These specify maximum additional waiting times for vessels to be levelled. A maximum of two vessels can be locked simultaneously. If a (second) vessel is not expected within the prescribed waiting time, the lock will be levelled with only one vessel. In the case of traffic appearing on the other side of the lock, the lock can also be levelled empty. The nautical traffic model runs two weeks to resemble a short drought, generating a trade-off curve between vessel delays and saltwater intrusion mass.

3.3 Model outcomes

3.3.1 Open systems: cascading effects due to tidal downtime and berth congestion

For the open system case, OpenTNSim results in a time-distance diagram, as presented in Figure 3.5a. The background colours indicate the maximum allowable draught at a given location over time. They correspond to the water depths at the nodes (see Figure 3.5c). The horizontal tidal restriction results in additional tidal windows (see Figure 3.5b). These correspond to periods when the current velocity restriction is not exceeded (see Figure 3.5d).

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In Figure 3.5a, the LR2 vessel arrives during a rising tide within a tidal window. The vessel requests access to the terminal, which is granted since it is not occupied. Furthermore, vessel LR2 requests to enter the port, which is also granted as it is possible to have a safe transit within an available tidal window. Therefore, the vessel can immediately proceed to the terminal, where it will be handled for 4.7 days. At the moment when the handling is almost finished, the LR1 vessel arrives at the port. This vessel can request access to the terminal with pre-emption, as the LR2 vessel will have left the terminal once the LR1 vessel arrives (when vessel LR2 finishes (un)loading, its request to leave the port is granted as there is a tidal window). Therefore, the request for the terminal access of vessel LR1 is accepted and also the request for port entry is granted, as the vessel arrives within a horizontal tidal window (recall that this vessel does not have a vertical tidal window). Hence, vessel LR1 arrives at the terminal and starts (un)loading for 3.8 days. Once it finishes (un)loading, it requests to leave the port, which is granted as it falls within the horizontal tidal window. Therefore, it releases its request for terminal access, making the terminal available again for the next vessel. In this scenario, it can be observed that there is no waiting time for either vessel.

When the same scenario is simulated but with a slightly delayed arrival time for both vessels, waiting times emerge, as can be seen in Figure 3.6a. First, there are waiting times for vessel LR2 due to draught limitations. As the arrival time falls outside of a tidal window, the request of vessel LR2 for port entry cannot be granted by the vessel traffic service. Later, after the vessel finishes (un)loading, its request to leave the port cannot be granted either, because the time of the request is outside of a tidal window again. It waits for the rising tide to sail through deeper water (between the contour lines corresponding to a maximum draught of 15 m). Second, due to the delayed arrival and departure of vessel LR2, there is congestion-related waiting time for vessel LR1, as its request to access the terminal cannot be granted since it is occupied by vessel LR2. Hence, it has to wait in the anchorage area until the terminal becomes available. In total, vessel

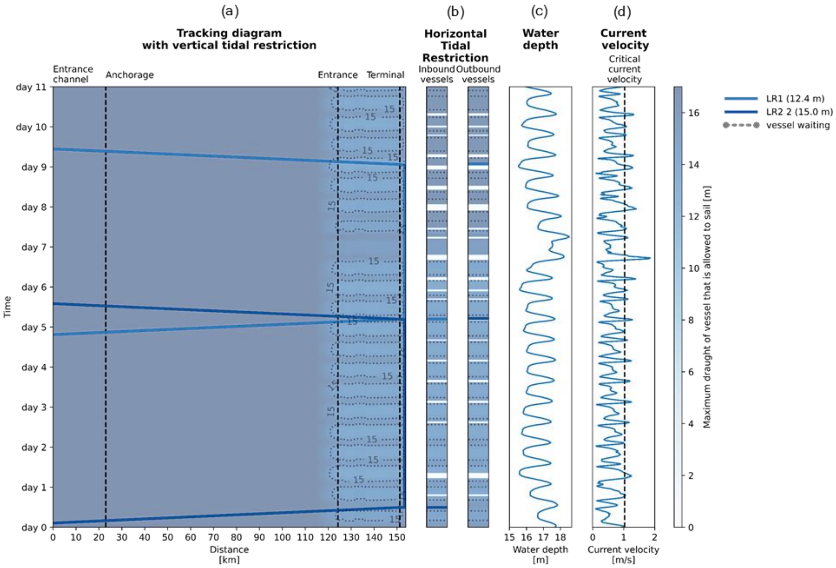

Figure 3.5: Results of the simulation run without the influence of tidal windows: a time-distance diagram (a), the horizontal tidal restriction (b), water depth (c), and current velocity (d) near the harbour basin of the liquid bulk terminal.

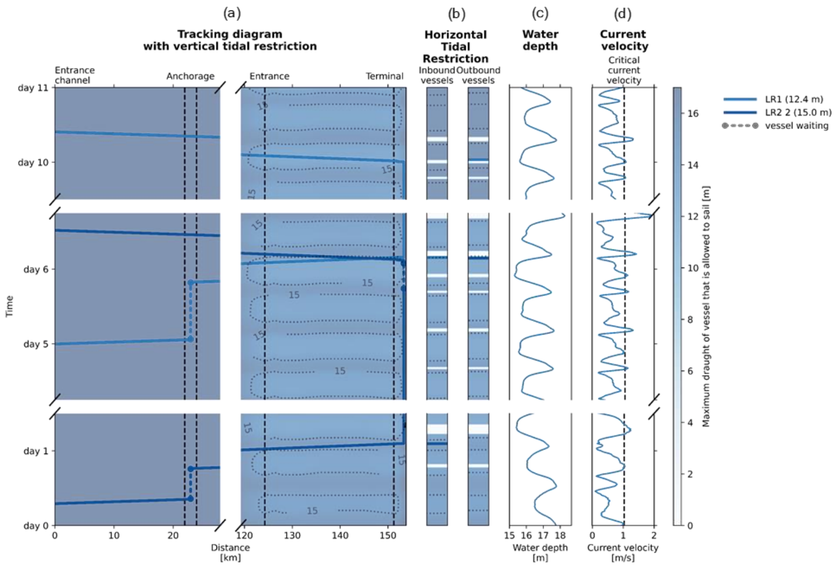

Figure 3.6: Close-up of the results of the simulation run with the influence of tidal windows: a time-distance diagram (a), the horizontal tidal restriction (b), water depth (c), and current velocity (d) near the harbour basin of the liquid bulk terminal.

LR2 waited 9.8 hours before it could enter the port, and 7.3 hours before it could leave the port, resulting in a total waiting time of 17.1 hours for vessel LR1.

With the above two scenarios, it can be observed the cascading effects emerge between tidal downtime and congestion. Hence, these must be resolved by a quantification method to accurately model vessel waiting times.

3.3.2 Closed systems: delays at locks

A typical lock passage, as predicted by a nautical traffic model based on the OpenTNSim library, is presented in Figure 3.7. In Figure 3.7a, one can observe an inbound vessel arriving and slowing down to enter the lock chamber. The door closes while the vessel is berthing. When both processes have been finished, the lock is being levelled. In the meantime, an outbound vessel arrives at the lock and waits in the line-up area to enter the lock after the current lock operation has been finished. After the lock door has been opened, the inbound vessel de-berths and passes the outbound vessel. This outbound vessel can subsequently enter the lock chamber and the process is repeated. The quantification method results in door opening, levelling, and door closing, which are marked in Figure 3.7.

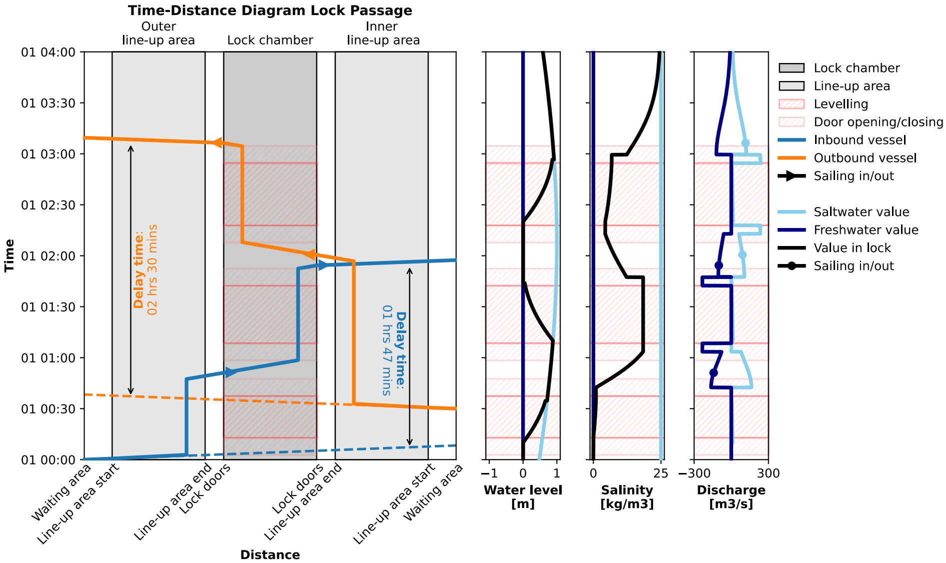

Figure 3.7: Simulation result of a two-way lock passage: a time-distance diagram of the inbound and outbound vessel (a), the water levels (b) and salinity concentrations (c) of both harbours and the lock chambers, and the fresh- and saltwater (brackish) fluxes through the lock doors.

In Figure 3.7b, the water levels at both harbours and in the lock chamber are shown over time. The lock chamber follows the water level of the harbour to which the door has been opened. The levelling time depends on the water level difference. The salinity of the lock in Figure 3.7c varies between the salt concentrations of the harbours. While the door is open at the seaside, the salinity of the lock chamber gradually increases. The effect of the vessels leaving the lock can also be observed; the vessel's volume will be replaced with salt- or freshwater, increasing or decreasing the salinity of the lock chamber. Also, the levelling with saltwater (when the water level at sea is higher than the inner harbour), increases this salinity. The corresponding exchange discharges are shown in Figure 3.7d. The assumption regarding the separation of the individual events in the Zeesluisformulating can be observed: the volume of the vessels sailing out of the lock chamber is replaced instantaneously, before the exchange current will occur, followed by the instantaneous replacement of water as the total volume of vessels sailing into the lock chamber. The latter two discharges cause the saltwater intrusion flux at the inner harbour. Note that because of these assumptions, the moments of sailing in/out in the Zeesluisformulering are not aligned with the nautical traffic model.

3.3.3 Clustering: vessel delays vs freshwater availability

In Figure 3.8, the trade-off curve between the salt intrusion mass and the average delay time of vessels as a function of the maximum clustering time is presented. Recall that the maximum clustering time is the time that a vessel will wait for another vessel to arrive, provided the second vessel is expected to arrive at the lock within this time. It can be observed that saltwater intrusion mass flux decreases with clustering time. This is because the clustering results in fewer lock operations: 316 lockages (without clustering) to 235, 208, and 196 operations for one, two, and three hours of maximum clustering time, respectively. Note that about every $0.5 \cdot 10^8$ kg of intruded salt mass equals 10 fully exchanged lock chambers filled with sea water with a salinity of 25 kg m^{-3}. Furthermore, as a consequence of the decrease in lock operations, the delay times of vessels will increase exponentially with increasing clustering times. This behaviour is caused by cascading effects: during the additional waiting time of vessels in the lock chamber, vessels on the opposite side must also wait, further increasing the average lock passage time. Initially, there is a small decrease in the average delay time of vessels if the maximum clustering is limited by an hour, as one-to-one locking of vessels decreases the lock capacity. The nautical traffic model predicts that increasing the clustering time to over three hours does not lead to more delays or less saltwater intrusion, as maximum lock occupancy is achieved.

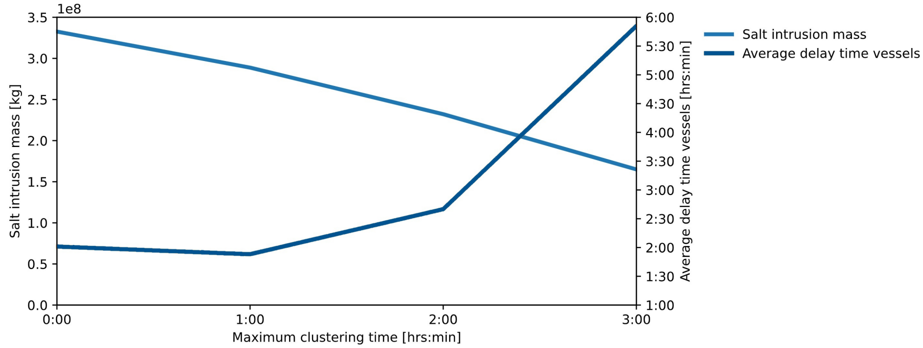

Figure 3.8: Trade-off curve between the salt intrusion mass and the average delay times of vessels in hours, as a function of the maximum clustering time in hours

With the Zeesluisformulering, it could be calculated that around 90% of the intruded salt mass flux occurs during the exchange flow when the lock door is open. The majority of the remaining flux is caused by the vessels sailing in from the inner harbour side. Emptying the lock to the inner harbour side has only a marginal effect on the saltwater intrusion in this specific case. Moreover, the relative increase in salinity in the lock chamber during filling with saltwater (when the sea level is higher than the inner water level), and subsequently the lowering of the lock's water level by discharging salty water in the canal, was negligible. The most efficient way to reduce saltwater intrusion in this example is to limit the door-open times. Although this was not applied to the model, it could have resulted in a significant reduction in the values presented in Figure 3.8.

3.4 Discussion

3.4.1 Open systems

Vessel waiting times can increase significantly, depending on the moment of arrival of the vessels. This is due to the tidal windows. Thereby, it generated cascading waiting times for vessel LR1, which itself is not subject to tidal windows. Tidal windows can lead to extra congestion due to causality. The additional waiting time on arrival of vessel LR2 led to extra waiting time on departure. Considering these cascading effects, this demonstrates that nautical traffic capacity and MBL design are interconnected. Hence, MBL designs that are solely based on individual vessels may be sub-optimal. Thus, the nautical traffic modelling method implemented in the OpenTNSim library is now available to quantify these effects on the impact of changes to the physical system, such as interventions in the MBL designs, on vessel waiting times. This is valuable for policy and decision-making in areas where waterborne transport is a major stakeholder.

This chapter only presented a simple case study. However, it showed that the mesoscopic agent-based nautical traffic modelling method implemented through the OpenTNSim library is well capable of researching more complex situations. This can involve fleets of different vessel types calling at a port with multiple terminals, anchorage areas, and turning basins. Furthermore, complex tidal window policies and traffic regulations can be included in the quantification method. In further research, to make more accurate and justified predictions, extensive calibration and validation of the method should be performed based on an elaborate analysis of shipping data from AIS. These developments allow the OpenTNSim library to be applied in policy- and decision-making. Moreover, it can be used for other operations and strategic purposes, including various KPIs related to capacity, efficiency, safety (van der Werff *et al.*, in rev.) and sustainability (van der Werff *et al.*, in rev.). Examples include the optimisation of nautical traffic policies and port infrastructure, and the impact of changes in the hydrodynamic system on nautical traffic and other non-port-related stakeholder functions (see S. R. Iglesias (2022)).

3.4.2 Closed system

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Clustering can be an effective measure to limit saltwater intrusion. However, the question arises whether the same results would apply to a real case study, as the nautical traffic model makes various simplifications and assumptions. The application presented in this chapter assumed a uniform interarrival distribution of a homogeneous fleet with constant vessel parameters (e.g., the sailing-in and sailing-out speeds of vessels, priority), and a lock complex with a single lock chamber. In reality, the lock complexes may consist of multiple locks with different interarrival distributions and vessel properties. The OpenTNSim library can account for this. Successful calibration of the vessel delays that have to pass locks with multiple lock chambers has been performed using AIS data (Kuiper, 2022). Operational data, such as the Object Data Services (ODS[6]) data from Rijkswaterstaat, can be used to calibrate the door-open and levelling times. More features to the library are yet to be added, such as explicit priority rules and vessel-dependent sailing speeds. The open-source nature of the library helps to speed up this development. The hydrodynamic part of the model also includes major simplifications. First, the salt concentrations are assumed to be uniform over the depth and width of the lock chamber and harbours. In reality, there is a more stratified salt concentration structure with complex mixing processes that affect the total exchanged salt mass. Second, the different exchange flux mechanisms are decomposed and are modelled sequentially. For example, the sailing-in and sailing-out of vessels, in reality, occur simultaneously with the exchange current between the fresh- and saltwater. The total effect of these assumptions should be further investigated using measurements of salt concentrations around locks.

This research was limited to the application of the coupled method to model the near-field salt intrusion fluxes only and the delay times of vessels. The next step is to translate these fluxes into the system-scale stakeholder objectives (i.e., freshwater availability based on the salt concentrations further inland). The obtained time series of discharge and salinity, including the specific door-open and levelling times, are well-suited to be included as boundary conditions in a numerical model. Such hydrodynamic models can even be coupled online, allowing the actual predicted salt concentrations at the outer and inner harbours to be used in predicting discharges and salt fluxes in the Zeesluisformulering. This is critical as more lock operations will result in a more brackish inner harbour and a fresher outer harbour. The application of the method did not yet include

[6] https://www.magazinesrijkswaterstaat.nl/zakelijkeninnovatie/2019/01/samenwerking

this. In addition, the impact on vessel delay should be modelled in system-scale nautical traffic models; further cascading waiting times are expected due to interaction with port and waterway congestion.

The coupled OpenTNSim library and Zeesluisformulering method enables quantifying the impact of navigation lock operation strategies and lock design on the physical system and stakeholders' performance, including waterborne transport. This paves the way for objective and transparent policy and decision-making in closed systems.

3.5 Conclusion

This chapter is motivated by several identified shortcomings of the quantification method provided by the OpenTNSim library, which was found to be most promising in assessing the impact of changes to the physical system on waterborne transport performance. Although the method could simulate the nautical traffic dynamics of a fleet of vessels that move as agents over a waterway network, it did not account for the processes of tidal downtime and congestion. For this, the method lacked realistic hydrodynamics and port layouts. It also did not account for tidal accessibility and berth-allocation policies, traffic rules, and detailed lock operations (see Chapter 2). These shortcomings inhibited OpenTNSim from fully quantifying vessel waiting times, the most KPI for waterborne transport, as they can exacerbate by cascading interactions between the above processes. Therefore, the quantification method was unable to be used in policy and decision-making in estuarine systems. This led to sub-question (SQ 2): *How can the most suitable quantification method be enhanced to more extensively include the interactions between waterborne transport and the physical system?*

In conclusion, additional modules can be added to OpenTNSim. Two modules have been added to account for the missing processes of tidal downtime and congestion in open and closed systems: the Seaport and Locking modules. The Seaport module includes a Vessel Traffic Service that communicates tidal windows and berth availability to vessels in advance. This is based on new algorithms that enable the inclusion of detailed tidal restrictions, berth allocation policies, port infrastructure, and realistic hydrodynamics. The Locking module operates as a navigation lock master that assigns vessels into lockages. It can predict vessel delay times and translate the lock operations into saltwater intrusion fluxes and freshwater losses using a coupling with the semi-empirical hydrodynamic modelling method of the Zeesluisformulering. Tests run showed that it is now effectively overcoming the earlier shortcomings. In open systems, the method can quantify the impacts of shallow MBLs on cascading waiting times due to the interaction between tidal downtime and berth congestion: smaller non-tidal vessels are affected by the tidal windows of larger vessels due to berth congestion. In closed systems, OpenTNSim can now assess the effectiveness of clustering vessels in the same lockage to limit the saltwater intrusion flux, while calculating the corresponding vessel delays. As expected, the salt intrusion flux is reduced with increasing maximum clustering time, leading to fewer lock operations, however, at the expense of an exponential increase in vessel delays.

Despite potential further improvements, the enhanced OpenTNSim library is a significant advancement over other existing quantification methods for modelling waterborne transport performance. For example, the method can overcome the current process of designing MBLs of waterways that are solely based on the accessibility of a deep-draughted design vessel. As significant cascading effects reduce the nautical accessibility of ports, the currently designed MBLs can potentially be suboptimal. Moreover, to the researcher's knowledge, the quantification method implemented through the OpenTNSim library is the only method that can study the simultaneous impact of lock operations on vessel delays and the physical environment. Further research on the method's development and validation with real-world data will result in an even more applicable tool that can be included in policy and decision-making. The validation of OpenTNSim for open systems is discussed in the next chapter.

4

Method validation: Cascading waiting times in the Port of Rotterdam

All nautical traffic models are wrong,
yet some can be very useful.

after George Edward Pelham Box

The previous chapter showed that controlling vessel waiting times is crucial for ports to be efficient and competitive. The impact of changes to the physical system on this waterborne transport KPI should, therefore, be included in policy and decision-making. Severe waiting times can be caused by cascading interactions between the nautical traffic and the physical environment, leading to congestion and downtime. To simulate these interactions, the open-source library of OpenTNSim has been evaluated as the most suitable development platform, although specific properties are lacking (Chapter 2). Chapter 3 describes two added modules that have been developed to resolve the system-scale interactions of fleets with the physical environment and port and waterway infrastructure. However, these algorithms have not yet been validated. This raises the following question (SQ 3): **How accurately can the quantification method replicate waterborne transport performance?** To answer this question, this chapter presents the validation of the nautical traffic modelling method, based on a hindcast study of observed waiting times of a fleet calling at an inland terminal in the Port of Rotterdam for the year 2019 — an open system. Geospatial, hydrodynamic, and AIS data are used to derive input parameters for OpenTNSim and to calculate laytimes in the anchorage areas for model validation. The hindcast study demonstrates that the nautical traffic model predicts the causes of 73.4% of the non-excessive waiting times of vessels, thereby correctly modelling 60.7% of the vessels calling at the port. Following a recent deepening of the access channel, cascading waiting times due to tidal restrictions were found to be limited. Nonetheless, the importance of the added modules to the OpenTNSim library is confirmed by testing alternative MBL designs. This chapter affirms the suitability of the implementation of the mesoscopic agent-based nautical traffic modelling method to quantify waterborne transport performance as a function of the physical environment in open systems.

This chapter is entirely based on a paper that has been published as: Bakker, F.P., Van der Werff, S., Baart, F., Kirichek, O., de Jong, S. & van Koningsveld, M (2024). *Port Accessibility Depends on Cascading Interactions between Fleets, Policies, Infrastructure, and Hydrodynamics.* Journal of Marine Science and Engineering. 12(6). doi: https://doi.org/10.3390/jmse12061006

The nautical traffic model is available under: https://zenodo.org/records/11489436

4.1 Introduction

In Chapter 2, it was found that an economically viable and competitive port and waterway system ensures the safe and efficient transit and operation of vessels. This means that vessel waiting times must be limited. Tide-related accessibility restrictions are a common cause of downtime, especially for the deepest-draughted vessels. A port can also be congested, meaning that the capacity of its infrastructure is overloaded. Port congestion and downtime are interconnected, which can lead to cascading effects that increase waiting times and, thereby, further decrease the port and waterway system's efficiency and competitive position.

To assess water transport efficiency, Chapter 2 found that the open-source library of OpenTNSim, which implements a mesoscopic agent-based nautical traffic modelling method to quantify waterborne transport performance, can be extended with dedicated modules for both open and closed systems. Chapter 3 outlined specific algorithms that have been added to this library to enable the quantification of cascading vessel waiting times by resolving the interactions between the nautical traffic system and the physical system. However, these algorithms have not yet been validated. Therefore, it is uncertain how accurately the quantification method can replicate the interactions between the seagoing traffic system and the estuarine system. To address this uncertainty, this chapter estimates vessel waiting times for a real-world case study using the updated OpenTNSim library and compares the simulation results with observations. If the amount of resolved waiting time is large enough, the proposed quantification method, and its OpenTNSim implementation, will be considered suitable to study the impact of physical system changes on water transport performance.

To perform the validation, the OpenTNSim is applied to resolve the nautical traffic behaviour of vessels calling at a liquid bulk terminal in the 3e PET in the PoR, which is connected to the sea by the NWW. This terminal is expected to exhibit the aforementioned cascading effects and involves vessels that govern the designed MBLs of the main access route. One year of AIS data is analysed, from which specific information is derived that serves as input for validation of the quantification method. The nautical traffic simulation is fed with the observed vessels and their arrival times and properties, such as draughts. Moreover, geospatial data is used which leads to a waterway network with the port infrastructure, along with average vessel speeds from the AIS data. Additionally, realistic hydrodynamic data is included, which is predicted by the in-house validated hydrodynamic model of the PoR. Thus, the nautical traffic model has all the ingredients to predict cascading waiting times. To validate these waiting times, they are compared with the observed laytimes in the anchorage areas, as derived from the AIS data. The simulation library is particularly useful as it allows us to unravel the underlying causes of the predicted waiting times, namely due to tidal restrictions, congestion of port infrastructure, and priority in berth allocation.

Section 4.2 provides the details of the case study and the data sources used. Section 4.3 describes the materials and methods required to set up and validate the nautical traffic model based on the OpenTNSim library. Section 4.4 compares the model results to the AIS data and demonstrates the method's potential through a brief study of alternative MBL designs for the NWW. Section 4.5 and Section 4.6 respectively, provide a discussion and our conclusions.

4.2 Case study

Before providing the details on the methods in Section 4.3, the case study is introduced in Section 4.2.1, and the data sources are described in Section 4.2.2.

4.2.1 Description of the 3e Petroleumhaven

The PoR is the largest seaport in Europe and serves as a transfer location for various types of cargo (mainly containers and liquid bulk) to other modalities bound for other destinations in Northern and Central Europe. An overview of the nautical infrastructure of the PoR is given in Figure 4.1. seagoing vessels arrive at the port's Traffic Separation System (TSS) through which they sail to the port entrance, possibly visiting one of the anchorage areas. There are three routes to the port entrance: a west-east corridor (i), a north-south corridor (ii), and a north-west-north-east corridor (iii). The southern (northern) and western (eastern) lanes are dedicated to inbound (outbound) traffic, while the deepest-draughted vessels make use of the central access channel, called the Euro-Maasgeul, and its dedicated anchorage areas. There are two deep-sea routes (A and B) that cross the TSS from north(-east) to south(-west).

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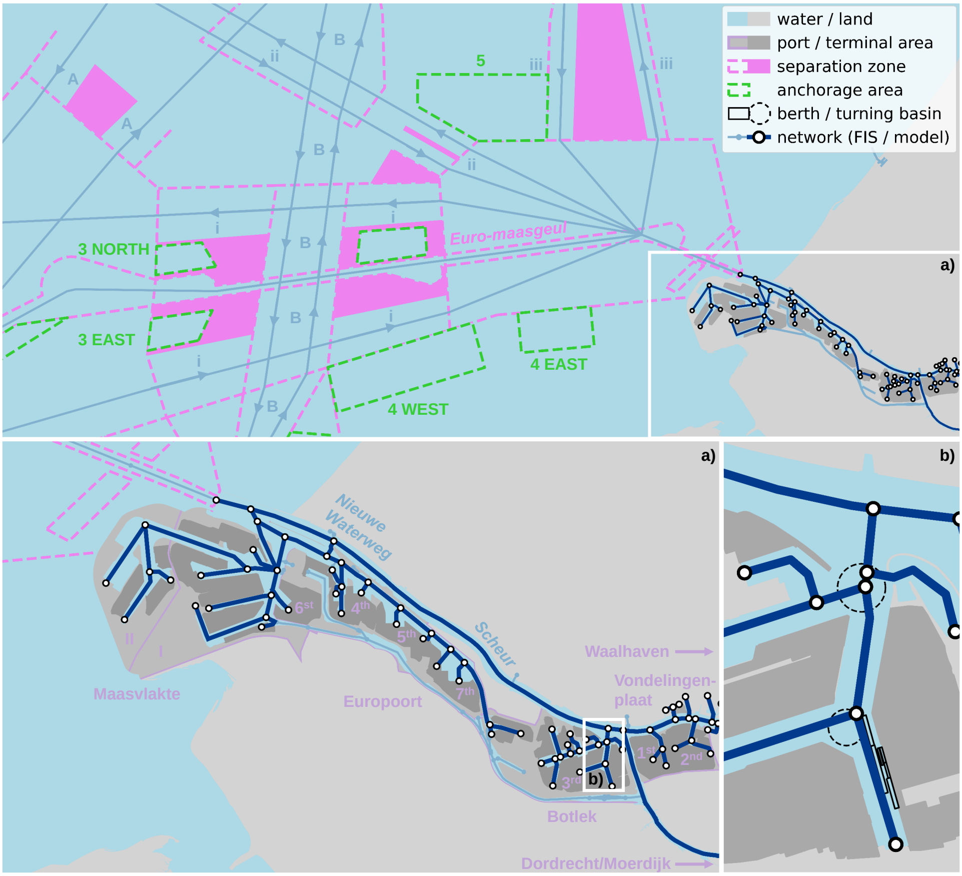

Figure 4.1: Nautical infrastructure of the PoR (**a**), including its TSS, and the 3e PET (**b**). The TSS consists of three routes to the port (i, ii, and iii); two deep-sea routes are crossing the system (A and B).

The 3e PET is an important transfer hub within the petrochemical cluster of the PoR. Constructed in the 1960s as part of the Botlek expansion, the basin is located along the main waterway, the NWW and Scheur (hereafter jointly called NWW), 21.5 km inland. Various terminals are located in the basin, facilitating both seagoing and inland vessels. The Botlek Harbour is an important hub as it defines the MBL of the NWW. In 2018, the NWW, and Botlek Harbour were deepened from 14.5 m to 16.2 m to facilitate partially loaded New Panamax and Suezmax-type vessels with a draught of up to 15.0 m. This research focuses on one of the liquid bulk terminals in the 3e PET that operates these vessels. It has various dedicated jetties and quays for deep-sea vessels, coasters, and barges, with varying MBLs and lengths.

To enter the 3e PET, vessels are subject to a tidal restriction policy. The regulations regarding the vertical (water level) and horizontal (current) tidal policy are summarised in Table 4.1 and Table 4.2, respectively. During navigation over the NWW, a vessel is obliged to have an UKC of 10% of its draught, increased by a FWA of 1.0% of the draught up to halfway along the waterway and 2.5% of the draught in the remaining part of the channel. The maintained bed level of the NWW is optimised for the deepest-drafted vessels (de Jong, 2020), based on this policy, and varies from 16.2 m MBL in the first half to 16.4 m in the second half of the channel. Given this information, vessels with a draught of 13.0 m or more are subject to a vertical tidal window. Additionally, some vessels are prone to a horizontal tidal window when entering the 3e PET. Vessels with a length of 180 m or more and a draught ranging from 11.0 m (inbound) or 12.0 m (outbound) up to 14.3 m are in principle only allowed to enter or leave when the tidal currents are less than or equal to 2.0 kn. Outbound vessels, however, are exempt from this condition during ebb tide, which is fully accessible. In contrast, vessels with a draught equal to and greater than 14.3 m are only allowed to enter or leave during flood tide when the currents are 0.5 kn or less (ebb tide inaccessible).

Table 4.1: Restrictions for vertically tide-bound vessels to the 3e PET based on entrance policy in the Port of Rotterdam

	Nieuwe Waterweg		**3ePET**
	km 0 - 10	km 10 - 21.5	km 21.5
MBL	16.2 m	16.4 m	12.65 - 17.0 m
UKC	10.0 %*	10.0 %*	0.5 m
FWA	1.0 %*	2.5 %*	2.5 %*

*as percentage of the draught of the vessel in [m]

Table 4.2: Restrictions for horizontally tide-bound vessels to the 3e PET based on entrance policy in the Port of Rotterdam

Direction	**Length**	**Draught**	**Tide**	**Condition**
In	≥ 180 m	11.0 up to 14.3 m	Flood Ebb	2.0 kn 2.0 kn
Out	≥ 200 m	12.0 up to 14.3 m	Flood Ebb	2.0 kn accessible
In & Out	n/a	≥ 14.3 m	Flood Ebb	0.5 kn* inaccessible

*only when currents are decreasing towards high water slack

4

4.2.2 Data sources

For this case study, the following data sources have been gathered: geospatial, AIS, and hydrodynamic data. These sources are required for the underlying approach of this work: the mesoscopic agent-based nautical traffic model to quantify waterborne transport performance, implemented through the open-source, Python-based OpenTNSim library (see Section 4.3).

Geospatial data

Geospatial data is a collective term for all data with a specified geometry. For the approach discussed here, the schematic representation of the port's wet infrastructure is of particular interest. On the one hand, this relates to the network of waterways, which is schematised in the quantification method as a graph, typically consisting of connected lines (edges) and points (nodes). Various geospatial processing tools, such as Shapely[1], are available in Python to derive such networks from shapes that mark the fairways and water bodies. Moreover, spatial-temporal processing tools, such as the Python-based MovingPandas[2], can derive networks by aggregating observed tracks in the AIS data (see Section 4.2.2). In many cases, more formal versions of such nautical traffic graphs exist. For instance, in the Netherlands, Rijkswaterstaat provides the latest information on the state of its waterways via the Fairway Information System (FIS)[3]. The network is also accessible in the software publication of Bakker *et al.* (2024). It follows the fairways with sufficient detail and is therefore used in the case study of the 3e PET (see Figure 4.1).

On the other hand, this relates to information on important port infrastructure, such as anchorage areas, fairways, turning basins, and berths. Generally, it is sufficient to specify such infrastructure in the form of shapes that specify their position and outline. In some cases, further metadata are needed, e.g., the capacity of an anchorage area or berth, and the applicable UKC

[1] https://pypi.org/project/shapely/
[2] https://pypi.org/project/movingpandas/
[3] https://vaarweginformatie.nl/

policy for a fairway section. Port authorities may also have accurate geospatial datasets including metadata that can be used. In this research the geometric extents of the 3e PET, the PoR and the areas of the TSS (see Figure 4.1) were obtained from OpenStreetMap[4] using the open data mining tool Overpass Turbo[5]. A polygon containing a specific area between the breakwaters, used in the AIS analysis in Section 4.3.1, was created using Google Earth. Specific geospatial data with metadata on MBL and FWA were obtained via PoR, through its Port Map application[6]. The geospatial data of the PoR are reliable, as they are used in daily operations. The data of OpenStreetMap were carefully validated using satellite imagery. While the geospatial data of the PoR are confidential, the open-source data are shared in Bakker *et al.* (2024).

AIS data

The AIS is an automatic vessel tracking system that is primarily used to guarantee safety in waters with heavy traffic. It consists of a time series of various types of messages that contain either static vessel properties (e.g. the vessel's unique Maritime Mobile Service Identity (MMSI) number, the vessel type, the vessel's dimensions) or dynamic vessel properties (e.g. location, Speed Over Ground (SOG), and Course Over Ground (COG)). The dynamic data are transmitted with a higher frequency than the static data; every 2–10 s a message is transmitted for a sailing vessel, increasing to 180 s for an idle vessel. By combining the static and dynamic components, the transit information of each vessel can be gathered, stored, and researched. Raw AIS data are available in National Marine Electronics Association (NMEA) encoding. The open-source Python package PyAIS[7] can be used to decode these raw data and convert them into readily usable DataFrames (i.e., Pandas[8]). Ready-to-use, pre-decoded, and cleaned AIS data products may, in some cases, be available from organisations like the coastguards, the local water authority, and port authorities. For this case study, AIS data for the whole area of the PoR (including the TSS) for the entire year of 2019 were provided by Rijkswaterstaat. They decoded and anonymised the data, and guaranteed its quality by extensive error removal. The anonymisation algorithm ensured that the vessels maintained a unique vessel ID. The data processing that was applied to these AIS data is discussed in Section 4.3.1. Although the data are confidential, the derived input data for the nautical traffic model can be accessed through Bakker *et al.* (2024).

Hydrodynamic data

Hydrodynamic data are required for the calculation of the vertical (water levels) and horizontal tidal windows (current velocities), where and if applicable. The data can furthermore be used to determine the vessels' sailing speed over water. A useful data source should specify this hydrodynamic data as a function of time in at least two strategic locations. Data from measurement stations could be interpolated to relevant locations, e.g., to key nodes of the nautical traffic network. More measurement stations increase the accuracy. Another option, that is used in this research, is the use of a well-calibrated and validated hydrodynamic model. The PoR makes current hydrometeorological data available via its Weather, Tides and Water Depths platform[9]. An important tool in this platform is the "Operationeel Stromings model Rotterdam (OSR)" model that calculates water levels and currents, while constantly being re-calibrated with the most recent measurement data. This hydrodynamic model calculates the present hydrodynamic situation and makes a 24-hour prediction. Furthermore, hindcast simulations can be made with the model, which was done for this case study. Hydrodynamic data on relevant locations were acquired by adding monitoring points to the model's computational grid. The confidential model output was made available in NetCDF files for further processing. The quality of the water level and current velocity data of the OSR can be guaranteed as the model is calibrated extensively up to a level that it can be used confidentially in daily operations.

[4] https://www.openstreetmap.org/
[5] https://overpass-turbo.eu/
[6] https://experience.arcgis.com/experience/0127b94d675f48dd80702b5b81be6020/?draft=true&org=portofrotterdam
[7] https://pypi.org/project/pyais/
[8] https://pypi.org/project/pandas/
[9] https://www.portofrotterdam.com/en/up-to-date-information/weather-tides-and-water-depth

4.3 Materials and methods

To decompose the waiting times for the liquid bulk terminal in the 3e PET of the PoR, the mesoscopic agent-based simulation method implemented through the OpenTNSim library is applied as a nautical traffic model to hindcast a period for which observed AIS data are available. The following information is required for the model setup, which can be derived from available geospatial data, AIS data, and hydrodynamic data (see Figure 4.2):

- a geospatial graph of the port network, including:
  - schematisation of relevant port infrastructure,
  - governing UKC policies,
  - priority rules and berth-allocation policies; and
- the calling vessels in the form of agents, including:
  - dimensions (i.e., length, beam, and draught), and
  - followed trajectories to derive:
    - origin-destination information,
    - speeds, and
    - laytimes in various port areas; and
- realistic hydrodynamics over the port network, including:
  - tidal elevations as a function of time and space, and
  - current velocities at critical locations.

Section 4.3.1 describes processing steps applied to the AIS data (Figure 4.2I). Section 4.3.2 describes the additional steps that are needed for simulation and validation (Figure 4.2II). Section 4.3.3 describes the nautical traffic model that was set up (Figure 4.2III).

4.3.1 Data processing

The decoded AIS data contain information on all types of vessels, including barges, tugs, and pilot boats which constitute the majority of the data received. For this validation study, the behaviour of seagoing cargo vessels is of primary interest. To arrive at the desired level of detail, the AIS data had to be filtered and 'trajectorised' — constructing paths out of points — and outliers had to be removed. For this sequence of algorithms, the basic principle of performing the most computationally demanding algorithms on as little data as possible was followed. The processing was performed using the multi-core Planetary Computer of Microsoft[10]. The data processing steps are described in the subsequent subsections and are published as code in Bakker *et al.* (2024).

Filtering of the AIS data

Figure 4.2a shows some initial filtering steps that were applied to arrive at the AIS data of interest. By filtering on vessel type, the overall dataset is reduced to cargo vessels and tankers. Next, a polygon is used — one that encompasses the access channel between the breakwaters — through which inland barges will not sail. This enabled further trimming down the dataset to only the seagoing cargo vessels that call at the port. A combined polygon encompassing the berths of the specific liquid bulk terminal in the 3e PET was used to select only those seagoing vessels that called at the liquid bulk terminal at least once during the entire year of 2019.

[10] https://planetarycomputer.microsoft.com/

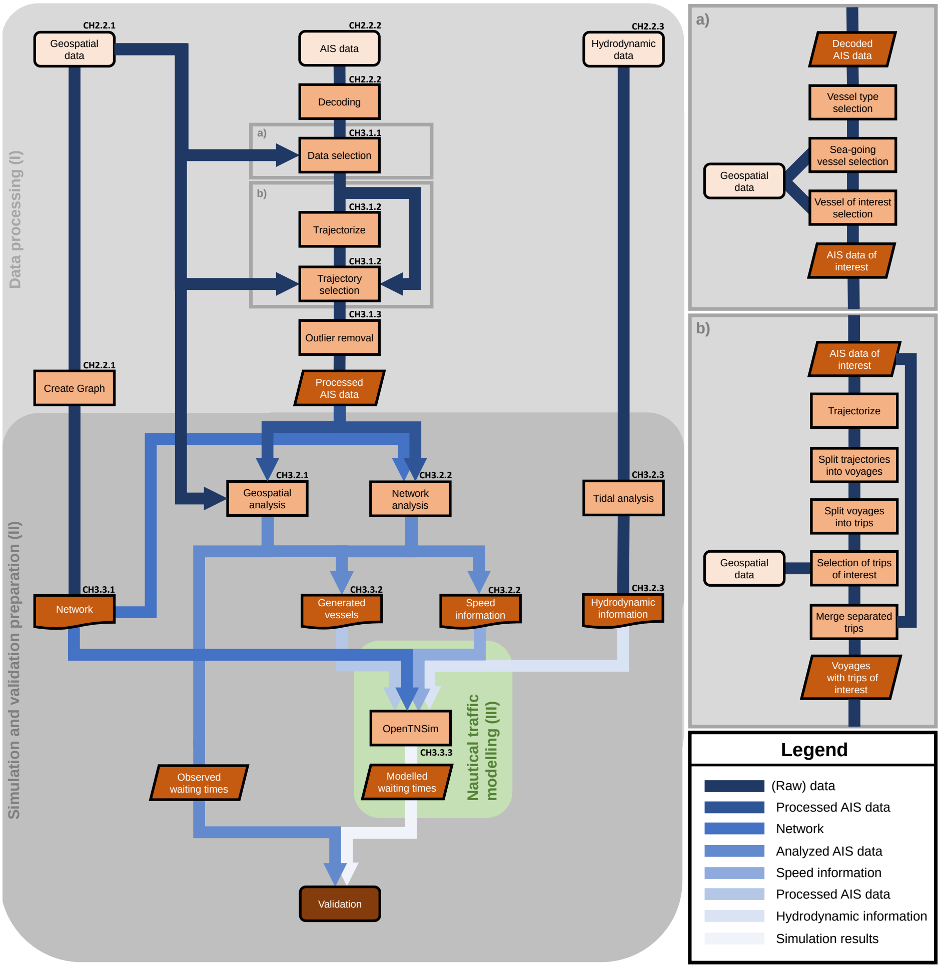

Figure 4.2: Information flows for the set-up and validation of the nautical traffic model, consisting of data processing (**I**), simulation and validation preparation (**II**), and nautical traffic modelling (**III**). Close-ups (a) and (b) schematise the processing steps in the selection and trajectorisation of the data, respectively. The symbols are according to the ISO standards.

Trajectorisation into trips and voyages

Next, Figure 4.2b shows the subsequent steps that were taken to process the AIS data. First, the now-filtered AIS data are trajectorised based on a unique static vessel property (i.e., vessel name). For each vessel, this resulted in a tabulated chronological overview of all time-position combinations in the 2019 AIS data. For each time-position combination, instantaneous vessel properties like speed, heading, and acceleration were added to the table for later use. Since the total trajectory of one vessel for a given year generally consists of several voyages (or port calls) that, in turn, can consist of multiple trips (origin-destination combinations), the next processing step is to split the vessel trajectories into 'voyages' and 'trips'.

A 'voyage' (or port call) is defined as a vessel's inbound and outbound time-of-stay within the port infrastructure, including the TSS. To distinguish between voyages, a time gap without any messages in a vessel's trajectory data is used. The open-source Python package MovingPandas provides the so-called ObservationalGapSplitter method for this purpose. A gap of 6 hours was applied to distinguish between voyages in a vessel's trajectory data. Each voyage was assigned a unique ID for later analysis.

A 'trip' is defined as a subset of a vessel's trajectory (or voyage) data, demarcated by a clear origin and destination. The start and stop of each voyage are taken as origin and destination, respectively. To distinguish between trips within each voyage, the time was used during which a vessel stays at a fixed location. The StopSplitter method of MovingPandas, can be used for this purpose. It creates splits based on the condition that a vessel stays within a certain radius for a minimum duration. Based on trial and error, a diameter of 25 m was used in combination with a minimum duration of 30 minutes to identify intermediate stops in each voyage. Each trip was assigned a unique ID for later analysis.

As the StopSplitter operation proved to be time-consuming, the trajectory data of each vessel were separated into subsets of roughly equal size. This allowed for parallel processing, which greatly reduced the processing time. One artefact of this approach, however, was that artificial splits were created at the boundaries between the subsets. To resolve this, a merge step was required to rejoin sub-trips that belonged together. Another artefact was that the StopSplitter method deletes the trajectory data that fall within its search radius. As a consequence, the start and end points of subsequent trips would no longer match. In some cases, this caused significant shifts in a vessel's position from the end of one trip to the start of the next, which in turn caused problems in the subsequent analysis. To resolve this issue, the deleted data were retrieved and restored.

To focus on the inbound and outbound traffic of the 3e PET, the combined polygon of the 3e PET berths was used to reject all trips that did not stop or start in this area. The remaining trips were sorted by their start time, classified as inbound or outbound depending on their start and endpoint, and combined into round trips. If the inbound trip had one of the anchorage areas as its origin, the preceding trip with this anchorage as its destination was added to this trip. This resulted in 255 individual vessels that undertook a total of 481 unique voyages, consisting of one or two inbound trips to the 3e PET (depending on whether the vessel anchored in one of the anchorage areas) and a single outbound trip from this terminal. Vessel properties such as length, beam, and draught, as derived from the AIS data, were added to each trip dataset. The difference in draught between the inbound and outbound trips was added as the (un)loading quantity to each voyage.

AIS data outlier removal

Unfortunately, AIS data are known to contain errors. Some of the AIS fields rely on manual input, so human error is expected here. However, other fields rely on sensors, such as the vessel's location as a function of time, as well as its SOG, COG, and derived speeds and accelerations. The last data-processing step is to remove errors of this kind. Since this is a very time-consuming row-by-row operation, this step was performed at the very end on the minimum subset of relevant voyages and trips. The following four conditions for sailing vessels, proposed by Abreu *et al.* (2021), were used to classify whether a data point was considered anomalous: stop, drift, acceleration, and turning. Based on trial and error, the condition for sailing vessels was set to a speed of 2 kn minimum. Suspected outliers were removed accordingly.

4.3.2 Simulation and validation preparation

The processed data from the previous subsection can now be used to generate inputs for the nautical traffic simulation OpenTNSim and its validation. The code of the data-analysis steps is published in Bakker *et al.* (2024).

Origins, destinations and other trip data

The 'real-world' coordinates of origins and destinations can be extracted straightforwardly from the voyage and trip datasets. Next to origins and destinations, each simulation needs at least the following information for each calling vessel: arrival time, sailing speeds along the route, projected turning time in the turning basins, designated berth(s), and the (un)loading time at the berth(s). Also, the vessel's actual laytime at the anchorage area must be recorded to validate the simulation results.

The designated berths of call are determined using the stoppage data between the inbound and outbound trips. An algorithm counts the number of AIS points that fall inside the different berths and selects the berth with the most hits as the vessel's most likely berth of call. The unloading times at these berths are estimated from the stoppage intervals between the inbound and outbound trips. The time for (de)berthing is assumed to be included in these intervals.

Turning times are estimated using an algorithm that calculates the time spent in the turning basins during the vessel's voyage while it passes through. The algorithm selects the turning time with the maximum time of stay, as the vessel only needs to turn once during its voyage. This may be during its inbound or outbound trip.

The laytimes in the anchorage areas are determined similarly to the unloading times at the berth, though with the start time of the second part of an inbound trip and the end time of the first inbound trip, starting and ending in the anchorage area, respectively. If the vessel did not visit an anchorage area, the laytime is set to zero.

Mapping locations to the graph

The nautical traffic model requires the origin and destination nodes for each trip, rather than the 'real-world' coordinates, to enable routing on the network graph. To map the trajectories of the AIS trips onto the routing graph, an algorithm was used that finds the nearest directional edge in the graph for each coordinate of the trajectory. Since this is a time-consuming operation for large amounts of data and complex, extensive networks, the algorithm was initially only applied to special waypoints. These waypoints were derived based on a running criterion on cumulative distance (1000 m) and cumulative course difference (30°). Based on the identified nearest directional edges of two consecutive way-points, a significantly smaller sub-graph could be defined, which was used for the search of the nearest directional edge for the coordinates between those way-points.

The origin and destination nodes of the trips were determined through a similar nearest-node algorithm. Accordingly, the timestamp of the AIS message closest to the origin node of the first trip was set as the arrival time at the port of the vessel. Vessels may originate from, or are bound for, another location within the port; the origin and destination of a voyage are not necessarily at the TSS. Since it was decided to omit the modelling of traffic in the TSS (see Section 4.3.3), for those vessels that did arrive from, or depart to, this area, the origin (including the arrival time) or destination to the node was set at the port entrance between the breakwaters. The observed arrival times of the vessels at this newly defined port entrance are of vessels that were cleared by the vessel traffic service to enter the port, as vessels originating from the TSS will wait in an offshore anchorage area for a tidal window and berth availability. Hence, to be able to quantify and resolve the waiting times in the anchorage areas, the arrival times had to be corrected (brought forward) for the time that the vessel waited in the anchorage area. Thus, if a waiting time is required for a vessel, it will be ordered to wait at the port entrance in the nautical traffic model.

Now that the actual routes of the vessels are mapped onto the graph, speed distributions can be identified for each directional edge that was covered by the vessels of call. For the simulations in the validation, it was assumed that vessels maintain their average speed over the edges. However, since the routes on the graph and AIS trips do not map exactly in space, the actual average speed of the vessel differs from the average vessel speed over the edge. For this validation study, it can be concluded that the vessel's average speed over the edge provides the most accurate results, meaning that the edge length, arrival time at the edge, and departure time from the edge are used to determine the average network speeds. This information was added to the graph so that it would be available for the vessels during the simulation. The vessel speed over the network is important for calculating the tidal windows. The slower the vessel sails, the smaller these windows will be.

Adding tidal information to the graph

Next to speeds, the simulations also require hydrodynamic data to be available on the network's nodes to enable the determination of tidal windows. Table 4.1 shows that different tidal restrictions apply for flood and ebb tidal periods. Determining the start and end times of these periods requires a tidal analysis of the hydrodynamic data. A tidal component analysis (or: Fourier analysis) was performed on the water levels and current velocities to obtain astronomical tidal data, using the

Hatyan package[11]. Next, a Principal Component Analysis (PCA) was applied to the data's current velocity magnitudes and directions to derive the main tidal directions. The intersection points of this principal tidal data with the abscissa (current velocity magnitude = 0 kn), resulted in the tidal periods — i.e., based on the slack tides.

4.3.3 Nautical traffic model

The OpenTNSim-based nautical traffic model's input consists at a minimum of the waterway network and the generated vessels with their routing information and realistic properties. To include tidal downtime and congestion in the model, the following network-specific details need to be incorporated: accessibility policies (such as tidal restrictions and vessel-priority rules), average vessel speeds per edge, hydrodynamic data at key nodes for determining tidal windows, and the port infrastructure (including anchorage areas, turning basins, and berths). The details of the nautical traffic simulation are discussed according to Figure 4.3. The derived input data (apart from the confidential hydrodynamic data) and setup of the nautical traffic model can be consulted in the software publication of Bakker *et al.* (2024).

Port infrastructure network

The waterway network in Figure 4.3 was extracted from Rijkswaterstaat's FIS that includes the PoR area (see also Figure 4.1). For simplicity, the TSS was not included. The complex vessel behaviour in the TSS is challenging to mimic and is assumed to not affect the waiting times of the vessels that sail to the 3e PET. Since the TSS contains (the routes to) the anchorage areas, a virtual anchorage area was placed at the port entrance to serve as the vessel waiting area. Vessels originating or departing to the TSS were modelled to be bound from/to the port entrance between the breakwaters. The arrival times of the vessels were corrected accordingly (see Section 4.3.2).

The port infrastructure that was added to this network consists of the port entrance on the most seaward node with the virtual anchorage area, the waterways towards the Botlek area schematised as nodes and edges, the dedicated turning basin for the 3e PET (for vessels up to a length of 290 m) on the penultimate node, and the liquid bulk terminal in the 3e PET on the last edge with its various berths for seagoing vessels. The turning time does not contribute significantly to the total turnaround time; however, vessels waiting for other vessels to turn or to pass the turning basin before they can turn can minorly contribute to the waiting times of the vessels.

Key properties of these objects were specified using the OpenTNSim mixin classes. Anchorages, waterways and turning basins were modelled using the 'HasResource' mixin. The virtual anchorage area is assumed to have an infinite capacity to prevent vessels from entering the anchorage area and leaving the port without being processed. The waterway edges were also assumed to have an infinite capacity, and they were modelled as bidirectional edges to account for two-way traffic. It was assumed that a safe distance is maintained by the vessels so that encounters do not lead to a reduction in speed. Overtaking by the seagoing vessels is assumed not to occur, as these vessels are sailing over the network with similar speeds. The turning basin can handle one vessel at a time, and the manoeuvre of the vessels is modelled to occur during the inbound trip. Outbound vessels can still occupy the turning basin, as they have to pass through it when leaving the port. The berths of the liquid bulk terminal are modelled using the FilterStore class from SimPy [12] (see Chapter 3). This concept works as a store of products (berths) with each having its properties, such as a name, a MBL, and a maximum vessel length that they can accommodate. The liquid bulk terminal has a few quays that do not have a unit capacity, like jetties, but instead have a finite length. However, these quays contain a limited number of fixed pumping facilities and are therefore modelled similarly to jetties. For simplicity, empty berths were assumed to be present at the start of the simulation.

Water level data were added to relevant nodes, and the governing MBL and the UKC policies were added to the edges (see Figure 4.3). Current velocity data were included at the critical point along the route where the vessels turn (KM 1015 at the Scheurkade). The water level and current information are used to calculate the tidal windows according to the governing rules that are summarised in Table 4.1.

[11] https://pypi.org/project/hatyan/
[12] https://pypi.org/project/simpy/

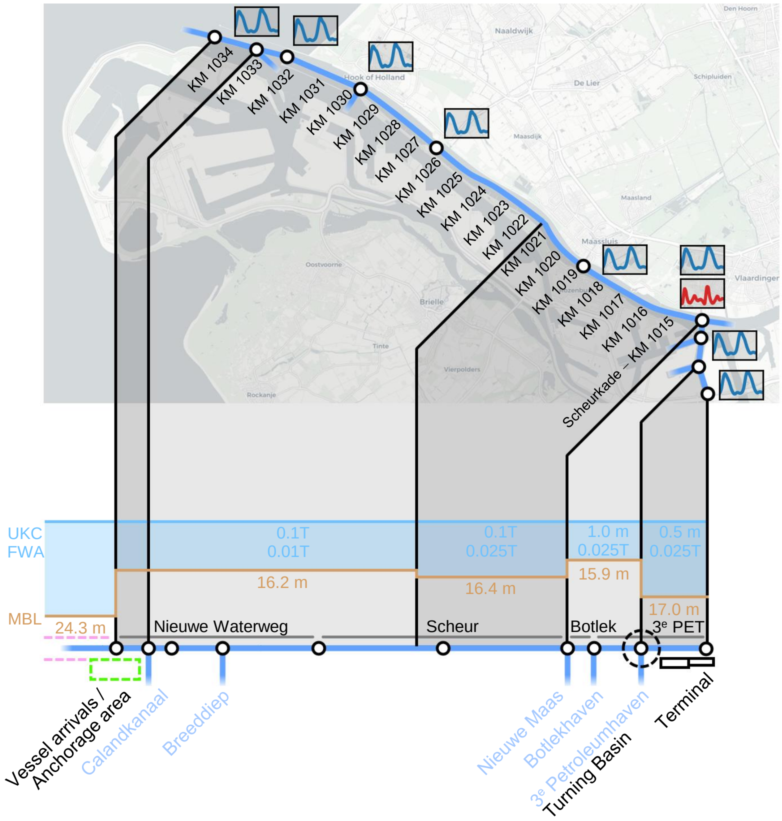

Figure 4.3: Overview of the nautical traffic model based on a section of the graph following the route to the 3e PET. The MBL, UKC, and FWA policies are added, which may be constant or dependent on the draught (T) of the vessel. The water levels (blue time series) and current velocities (red time series) are added to the nodes of the network.

Generated vessels

For the implementation of OpenTNSim, vessels have to be generated with the following required information:

- length and draught per trip in the voyage,
- origin, intermediate waypoints, and destination nodes that constitute the route of the voyage and trips over the network,
- arrival time at the vessel's origin node,
- designated berth(s) of call,
- turning time in the turning basin,
- the (un)loading time(s) at the designated berth(s), and
- the change in draught at the berths.

Since a hindcast study is performed, the observed traffic is replicated using the processed AIS data (see in Section 4.3.2). Each vessel travels past the nodes that are specified in its route. Between these specified nodes, the route is determined with Dijkstra's shortest path algorithm if needed. The route leads to the designated berth. In reality, berths can be assigned freely based on their properties and restrictions that prevent small vessels from berthing at the deep-sea berths (e.g., a minimum vessel length or draught requirement), which could also have been included in the model.

Modelling strategy

After the port infrastructure network and the generated vessels have been specified, the model determines how these vessels move through the network together. The simulation resolves where and when which vessel needs to wait and for how long. Waiting times in the anchorage area will occur if a vessel has to wait on either a tidal window or unavailable (congested) port infrastructure, either directly or indirectly through cascading effects. Priority rules to be included in the berth planning strategy to minimise the demurrage costs of vessels were omitted in this research but can be included in the model. Instead, the sporadically observed behaviour of newly calling vessels jumping ahead in the queue, over already waiting vessels, was mimicked by giving additional waiting times to these latter vessels. This waiting time equalled the difference between the arrival time of the two vessels and was presumed to be due to the priority rules. To quantify the individual contributions of the tidal restriction, berth unavailability and priority rules to the waiting times of vessels, as well as the cascading effects of these causes, the simulation was also run without tidal windows and prioritisation. Besides the reference situation, the model is applied to test alternative MBL designs for the NWW.

4.4 Results

First, the observations in the AIS data underlying the nautical traffic model, built upon the OpenTNSim library, and its validation are presented. Next, the results from the hindcast made with the model are described for validation.

4.4.1 AIS data

The processed AIS data are visualised in Figure 4.4. A total of 481 voyages were identified, made by 255 different vessels. 52.8% of these voyages were operated by vessels that can be classified as Coaster vessels, while 23.1% were of the Handysize class, 9.1% of the Handymax class, and 12.5% were vessels of the Panamax class. Only 2.3% of the voyages were made with New Panamax-class vessels and a single Suezmax-class vessel called at the terminal. From this dataset, it is also possible to derive origin-destination patterns and length-draught distributions. For example, 80.7% of the inbound trips used the NWW, of which 5.2% were tide-bound (83.3% of the total tide-bound vessels). Figure 4.5 shows histograms and distributions for the following key aspects of the observed traffic: laytime at the offshore anchorage areas, sailing times for inbound and outbound vessels over the NWW, turning times for inbound and outbound vessels, and laytime at the terminal. Figure 4.6 shows the distribution of speed over the network for vessel voyages that called at the liquid bulk terminal.

Laytime at the anchorage

The laytime of vessels at the anchorage area is used to validate the nautical traffic model. 39.7% of the voyages included laytime in the anchorage area. 89.5% of these voyages originated from offshore. Based on expert judgment, it is expected that voyages originating from other areas in the Port of Rotterdam would claim internal anchorage areas or, less likely, wait at their terminal, and only visit an offshore anchorage area if the internal anchorage areas or terminal are not available, or waiting in internal anchorage areas is impossible. Furthermore, 59.7% of the voyages with laytime in an anchorage used the closest anchorage to the port along their route, 4 EAST. 88.4% of these voyages arrived from the southwest. 13.1% of the voyages with waiting time used anchorage 5; all offshore trips arrived from the northwest. Out of the deepest-draughted vessels (14.8 m $\leq$ draught $\leq$ 15.0 m), the four New Panamax-class vessels were obliged to navigate the Euro-Maasgeul. Two of these vessels had laytime in the dedicated anchorage areas of 3 North and 3 South.

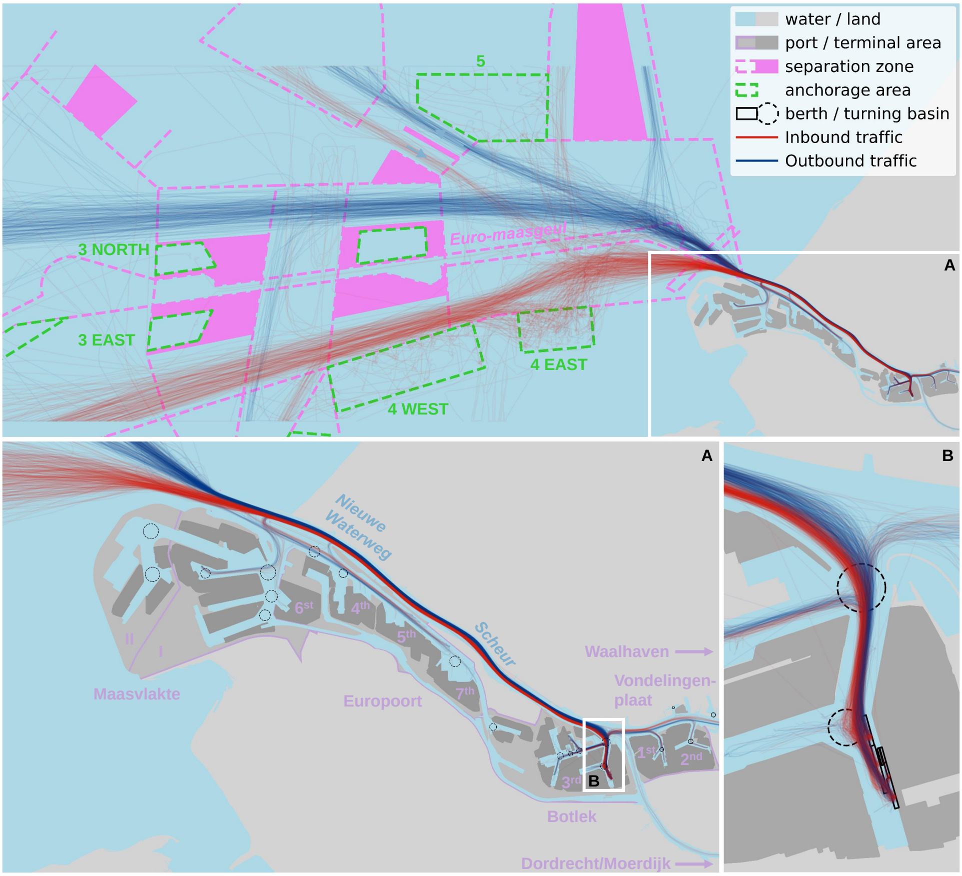

Figure 4.4: Overview of the processed AIS data shown as inbound and outbound trips of vessels that called at the specified terminal in the 3e PET. Two close-ups are added of the trips' track through the NWW (**A**) and the 3e PET (**B**).

From the probability density function (pdf) in Figure 4.5a, one can observe that 56.5% of the voyages that had laytime in the anchorage area did not wait for more than a day. Voyages with larger vessels tend to have shorter waiting times, as only 29.2% exceed laytimes of a day. The longest observed laytime was found for a New Panamax class vessel that waited over 13 days. The second longest was found for a Coaster vessel that waited almost 5 days. Laytimes of more than 2 days occurred frequently for voyages with smaller vessels (16.2%).

Sailing time

The sailing time over the NWW, presented in Figure 4.5b, is important for estimating the delay in arrival time at the terminal and determining the tidal windows in the nautical traffic model. It can be observed that the speeds contain significant spreading with transit times ranging from 50 to 120 minutes. Inbound vessels, on average, sail at lower speeds than outbound vessels; the modal sailing times are in the order of 75 and 65 minutes. This bias may be because most trips occurred during ebb tide, and because outbound vessels on average had less draught; larger vessels were observed to sail at lower speeds than smaller vessels, with modal differences of around 10

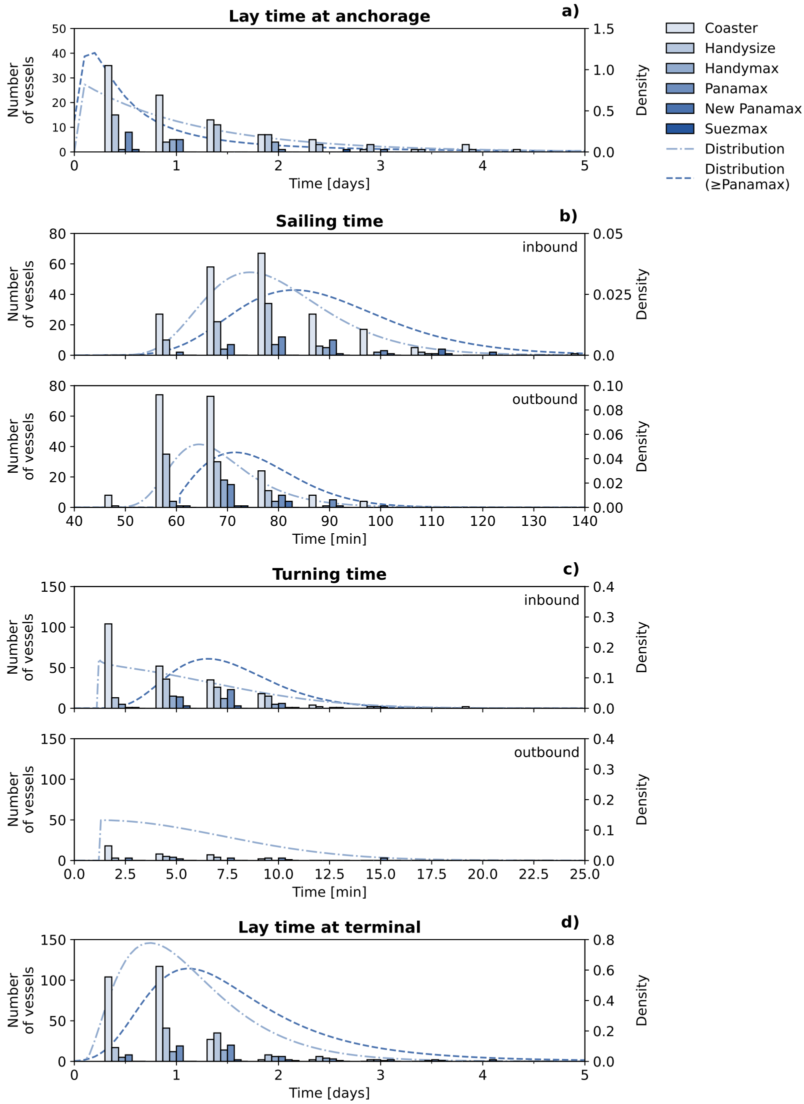

Figure 4.5: Histograms and distributions of the calibration data derived from the processed AIS data: laytime at the offshore anchorage areas (**a**), sailing time for inbound and outbound vessels over the NWW and Scheur (**b**), turning time for inbound and outbound vessels (**c**), and the laytime at the terminal (**d**).

minutes. However, an explicit correlation between the tide and the sailing speed was not found. The observed variation is expected to be due to, for example, captain behaviour, ambient traffic, the strength of (tidal) currents, and winds.

The aforementioned behaviour can also be seen in the average inbound and outbound speeds over the network, as shown in Figure 4.6. On the NWW, the average vessel speed is nearly constant: 9.9

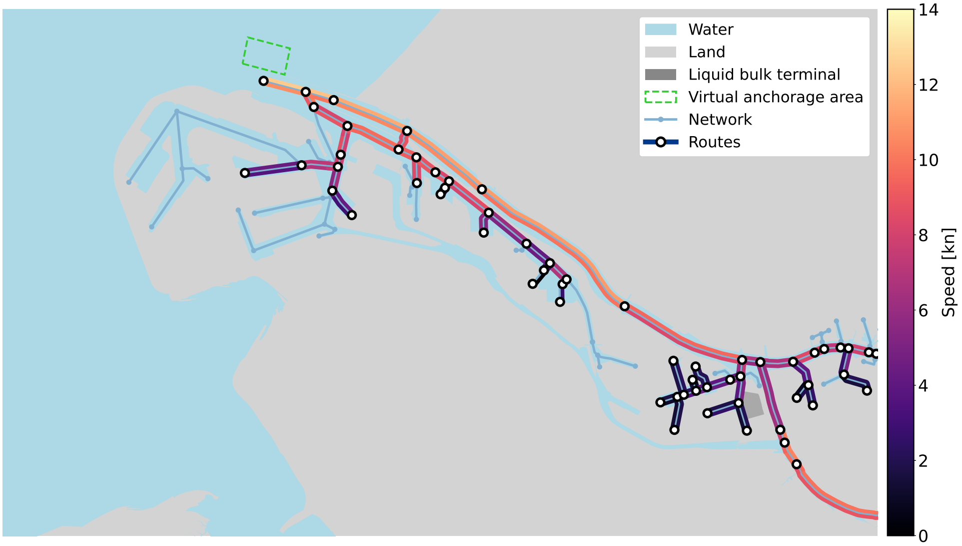

Figure 4.6: Speed distributions over network derived from mapped AIS data of the vessel voyages that called at the liquid bulk terminal. The coverage of the network corresponds with the tracks found in Figure 4.4.

kn for inbound vessels and 11.1 kn for outbound vessels. Towards the Botlek and the New Meuse, the average speeds drop due to decelerating (from 8.3 to 5.9 kn, on average) and accelerating vessels (from 7.4 to 9.5 kn, on average) that are respectively sailing in and out of the Botlekhaven. In contrast, at the entrance of the Port of Rotterdam, outbound vessels appear to accelerate further to 12.5 kn. Inside the harbour basins the average speeds are low, below 5.0 kn (in the 3e PET), as expected, and decreasing further towards the ends of the harbour basins as a consequence of complex vessel manoeuvres.

Turning time

Figure 4.5c shows the turning times of the vessels of call, i.e., when a vessel is occupying the entrance to the terminal and impedes other traffic from entering/leaving the 3e PET. They range from a minute up to several minutes with a maximum of 43 minutes (not shown in the figure). However, the pdf shows that 91.1% of the voyages have a turning time of less than 10 minutes. The turning times of vessels larger than Coaster vessels follow a positively skewed distribution, with a modal duration of around 6 minutes. Most vessels (84.2% of the total) turn during their inbound trip, in line with common practice, as this was previously mandatory based on safety regulations. There is no significant increase in the modal turning time with vessel size, although the longest turning times are observed for larger vessels. Most likely, the outliers are caused by severe winds. Since Coaster vessels are more manoeuvrable, most of these vessels are believed not to turn at the turning basin, but rather manoeuvre at the berth, passing the turning basin without actually turning. They significantly affect the overall distribution severely.

Laytime at the terminal

The time vessels spent at the berth is shown in Figure 4.5d. Note that during this laytime, the vessel occupies the berth, preventing other vessels from using it. The pdf follows a positively skewed distribution with a wide range, from a few hours to several days. The modal laytime of all vessels of call is slightly longer than a full day. For smaller vessels, especially Coaster vessels, the distribution shifts towards shorter laytimes of around half a day, while for the largest vessels

(Panamax class and larger) the distribution shifts towards longer times with a mode of around one-and-a-half days. Understandably, these differences are caused by varying transhipment volumes of liquid bulk between the vessel and the terminal, which increase with vessel size. However, the standard deviation is large compared to the average laytime for all types of vessels. Based on expert judgment, this is likely caused by varying onboard pumping capacities and the number of storage compartments that need to be loaded or unloaded.

Tidal restrictions

Figure 4.7 shows the draught and length combinations of incoming and outgoing vessels of call at the liquid bulk terminal. Only 4.9% of the inbound trips were affected by tidal windows during the voyage, while none of the outbound voyages were affected by a tidal window. During 83.3% of these trips, vessels experienced long-lasting horizontal tidal windows, based on a critical velocity. Only 10.0% of these vessels (with a draught greater than or equal to 13.0 m) had tidal windows further restricted by the vertical tidal constraint. For these vessels, the accessibility was fully determined by the criterion of the critical tidal velocity. The resulting tidal windows, combining the vertical and horizontal tidal windows, are visualised in Figure 4.8a for a vessel with a draught of 14.2 m. For vessels with such deep draughts, horizontal tidal windows are severely restricted by the vertical tidal constraint. This combination still resulted in sufficiently long tidal windows. 16.7% of the inbound trips restricted by the tide were affected by a narrow tidal window, consisting of a strict, governing point-based horizontal tidal window within a tight vertical tidal window (see Figure 4.8b). Only 0.6% of the inbound trips involved vessels with the maximum design draught of 15.0 m, which had to fully exploit the MBL design of the NWW. Based on the observation that the deepest-draughted vessels left the terminal with less draught, the terminal can be considered to be an import terminal. This claim is, moreover, further supported by the fact that most incoming Coaster vessels (with a draught up to 8.6 m and a length of 120 m) arrive with less draught compared to their departure.

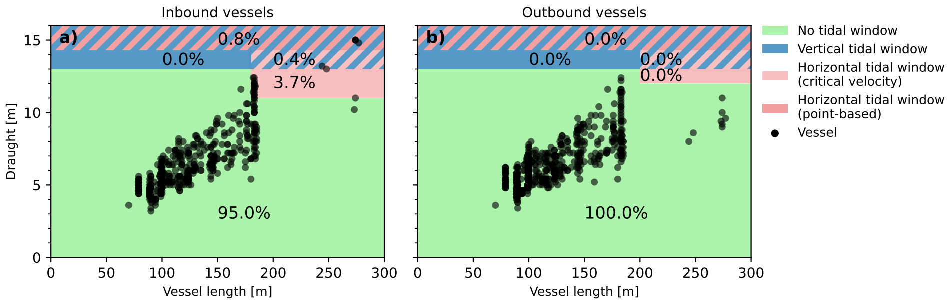

Figure 4.7: Tidal restrictions of the incoming (**a**) and outgoing (**b**) vessels, based on the vessel's length and draught, according to Table 4.1 and Table 4.2.

4.4.2 Nautical traffic model

Estimation of the total waiting time

A total of 481 voyages by 255 vessels, as observed in the AIS data, were simulated in the nautical traffic model. It was observed that 46.5% of the total laytimes in the anchorage areas were resolved (see Figure 4.9a); 53.5% of the observed laytimes, represented by the pink slices in this Figure (43.6% + 9.9%), were unresolved by the model. For 60.7% of voyages, the laytimes at the anchorage area were modelled with less than 10 minutes of difference from the observations. Additionally, the model correctly estimated the waiting time for 18.7% of other voyages with observed laytime in the anchorage area, although with some discrepancy. Hence, for the remaining 20.6% of voyages, the model could not resolve any of the observed laytime in the anchorage area.

For 99.0% of the correctly modelled voyages, the vessels did not have any observed laytime in the anchorage area, which was, hence, confirmed by the model. Furthermore, the model predicted

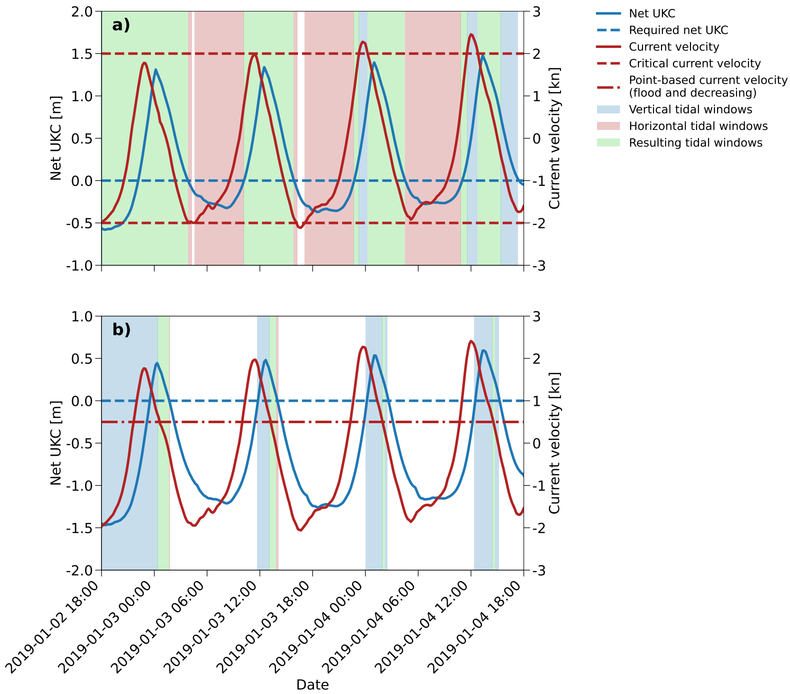

Figure 4.8: Examples of tidal window calculations: vertical tidal windows, governed by the net UKC (left axis; a positive value means excess water depth), with horizontal tidal windows based on a critical current velocity (**a**), of which the absolute should be smaller and equal to 2 kn during flood (positive currents) and ebb (negative currents), and a point-based current velocity (**b**), which should be 0.5 kn (during flood only) with a positive and negative spreading of both 30% based on practice (right axis).

that the observed laytime was exceeded only once. For this trip, no waiting time was observed, but the model estimated 6 minutes and 40 seconds of waiting time for a tidal window. The remaining 1.0% of the correctly modelled voyages were made by New Panamax-class vessels that did have observed waiting time in the anchorage area.

Underlying causes for the waiting time

From Figure 4.9, it can be observed that congestion due to berth unavailability (30.0%) contributes most to the resolved laytimes and is partly caused by prioritisation (14.0% + 1.2% + 0.8% cascading). Tidal restrictions (0.4% + 0.2% cascading) are of secondary importance for the laytimes. This is according to the expectations, as the NWW is designed for vessels with draughts up to 15.0 m, which led to only 4.9% of the vessels of the inbound trips being prone to tidal restrictions. As a consequence, cascading effects contributed to 1.0% of the resolved laytimes in the anchorage area. The unavailability of the turning basin did not result in additional waiting times, but this waiting time may be hidden in the additional laytime of vessels at the terminal.

The nautical traffic model indicated that 18.7% of the voyages were subject to waiting time due to terminal congestion. Most of these voyages were executed by Coaster vessels (53.3%) and Handysize-class vessels (33.3%), while the remaining waiting time due to berth unavailability was found for voyages made by Handymax-class vessels (4.4%), Panamax-class vessels (6.7%), New Panamax-class vessels (1.1%), and Suezmax-class vessels (1.1%). This distribution is skewed

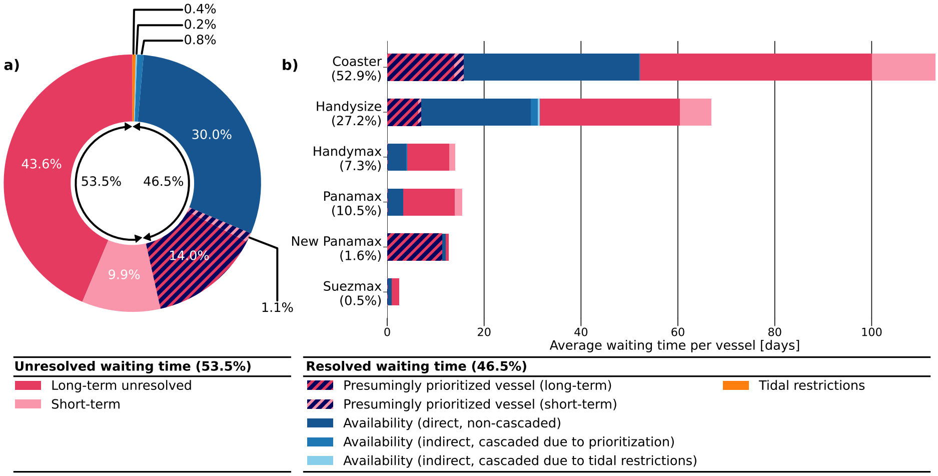

Figure 4.9: The causes of the total (**a**) and vessel type specific (**b**) laytimes of the vessels of call in the anchorage area for the base case and for the scenario without the inclusion of prioritisation.

toward the smaller vessels, compared to fleet composition (see Section 4.4.1). The main cause of this congestion was found to be the irregular arrival time of vessels, rather than the excessive laytimes at the terminal for some vessels, as observed in the AIS data. These extreme laytimes of more than 2 days, which caused other vessels to wait at the anchorage area, contributed to only 6.2% of the total waiting time due to terminal congestion. Although the underlying causes for the excessive laytimes at the terminal are not known, the majority are expected to occur when there is no active call for the specific berth at which the vessel is laying (idle). Unwanted excessive laytimes may have been caused by breakdowns in terminal equipment, vessel issues, or liquid bulk spills. However, these occurrences are infrequent.

During 36.7% of the voyages with waiting time due to berth congestion, the vessel likely gave priority to other vessels; during 8.5% of the total trips, a vessel moved ahead at the expense of another vessel. However, whether prioritisation is the main reason for this waiting time is debatable. This was confirmed by experts in the field, as the vessels are in principle scheduled according to First Come First Serve (FCFS). First, only half of the time ‘priority’ was given to a larger vessel. Secondly, long waiting times were observed — averaging more than 17 hours — for which prioritising is likely not beneficial. Third, significant waiting time due to prioritisation was observed for a New Panamax-class vessel, which waited over 11 days in the anchorage area. It was estimated that prioritisation was likely a motive for waiting in the anchorage area in only 1.0% of voyages, accounting for just 1.1% of the total observed laytime in the anchorage” for improved clarity and sentence structure, rather than the full 15.1%. In this case, cascading effects from prioritisation would not occur. It is assumed that none of the vessels gave priority in practice. Thus, this resolved vessel waiting time should be considered unresolved. A subsequent run without prioritisation showed that the resolved laytime of vessels in the anchorage areas decreased to 37.3%.

Only 1.2% of the total voyages were predicted by the model to have a waiting time due to the tidal restrictions, leading to minimal waiting time in the anchorage area. The horizontal tidal restrictions were found to be the primary constraint; 50.0% of the vessels that experienced waiting due to these restrictions were limited by a critical tidal current velocity, while the remaining 50.0% vessels experienced waiting time due to the strict point-based tidal window, with a maximum of 9 hours and 41 minutes. Since this contributed to 9.7% of the total turnaround time for that specific vessel, tidal accessibility remains important from an individual vessel perspective. Two of the four vessels, which were constrained by a strict tidal window of only 20 minutes per tidal wave, did not experience a wait longer than an hour. Therefore, it is expected that most of the waiting times in the anchorage area due to tidal windows are avoided through careful prior planning, to which vessels adjust their sailing speed at sea to arrive at the port during a tidal window.

Cascading effects were mainly triggered by vessels that presumably allowed other vessels to go ahead (prioritisation). Additionally, waiting times due to tidal restrictions led to further waiting times for non-tide-bound vessels.

Discrepancies with the observed waiting time

Accounting for only congestion (30.0%) and tidal windows (0.4% + 0.2% cascaded), 69.6% of the total observed laytimes in the anchorage area could not be resolved by the model. The observed discrepancies can be subdivided into long-term (43.6% + 14.0%) and short-term (9.9% + 1.1%) unresolved waiting times, separated for loading and unloading vessels (see Figure 4.10). These categories are discussed below based on feedback from experts at the PoR.

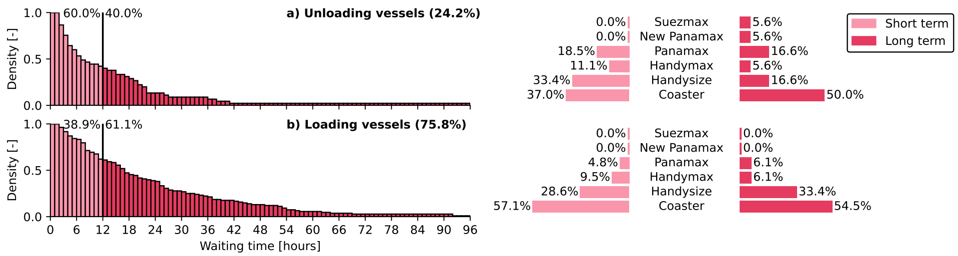

Figure 4.10: Inverse cumulative distributions of the discrepancies of unloading (**a**) and loading (**b**) vessels, including the number of vessels that had unresolved waiting times

In Figure 4.10, it can be observed that most unresolved waiting time is for loading vessels (75.8%) of which 61.1% is long-term, with an average waiting time of around 16 hours. Of the long-term waiting vessels, 94.0% are Coaster (54.5%), Handysize class (33.4%), and Handymax class (6.1%) vessels (see Figure 4.10b). A wide distribution of waiting times, including long waiting times, can be observed for vessels waiting to be loaded. These long, excessive laytimes are expected to be mainly caused by (a combination of) contractual obligations, and availability of the cargo/facilities at the terminal. For vessels hired by a party to load new cargo, sailing to the port as early as possible may be part of contractual obligations. These vessels arrive at the port and wait for the actual order to be fulfilled. Furthermore, as the terminal is processing the liquid bulk products, it may occasionally occur that the cargo is not yet ready to be shipped. Additionally, cargo may be lacking if the terminal is awaiting an import transhipment of another vessel. Since it can be deduced that the liquid bulk terminal is an import terminal, mainly smaller vessels are expected to be subject to these forms of waiting time. The shorter-term unresolved laytimes for loading vessels, which account for 38.9% of the total (see Figure 4.10), can also be explained by the above-mentioned processes. This form of waiting time is also dominated by smaller vessel classes (95.2%). Like the long-term unresolved waiting time, this is because larger class vessels constitute only 3.3% of the loading vessels. Therefore, these larger vessels contribute relatively more to the long-term unresolved waiting time, while the short-term contribution is more or less equal for vessels of all sizes.

In addition, it can be observed in Figure 4.10 that only 24.2% of the unresolved laytime is found for unloading vessels, of which 40.0% is found to be long-term. 27.8% of this long-term unresolved laytime is attributed to the Panamax class (16.6%), New Panamax class (5.6%), and Suezmax class (5.6%) vessels. These long-term unresolved laytimes may be related to price speculations and negotiations. In particular, the larger, loaded (to be unloaded) liquid bulk carriers may wish to anchor for an additional time as the market price for the transshipped cargo may rise. In addition to these speculations, negotiations about the final price may not have been concluded before the arrival of the vessel. An example is the Suezmax class vessel, which waited for an extra day and a half. Another reason for the long-term unresolved waiting time for the larger unloading vessels could be the unavailability of facilities at the terminal, such as the storage tanks. The long waiting time of 11 days for the New Panamax-class vessel may have been related to these reasons (see Figure 4.9). Smaller unloading vessels, which contribute 72.2% of the long-term unresolved waiting time, are also prone to these waiting times. However, most unresolved waiting times for unloading vessels of smaller classes are generally short-term and are more pronounced than the long-term waiting times. For the larger vessel classes, the unresolved waiting times are more or less equally divided between short- and long-term.

The (long-term) discrepancies can also result from a combination of frequent short-term disruptions, which constitute 60.0% of the unresolved waiting times for unloading vessels and 38.9% for loading vessels. First, based on interviews with captains of tanker vessels, conducted by Römers (2013), delays due to poor communication and coordination with the shore may cause small waiting times for vessels in the anchorage. For example, updates on berth availability are rarely provided to these waiting vessels. This leads to additional waiting times that are not accounted for in the model, as the communication in this model is assumed to be optimal. 40.0% of the vessels that would be loading at the terminal experienced a short-term unresolved waiting time of less than 4 hours, while having resolved waiting time due to berth congestion (see Figure 4.10a).

Second, congestion due to the limited availability of tugs and pilots occurs frequently in the PoR. This waiting time typically does not last longer than 2 hours and waiting for towage is reported to be the most frequent cause of waiting time (Nikghadam, 2023). During busy periods and extremely windy conditions, the increased demand for tugs and pilots may even cause waiting times of 3 to 4 hours. It is questionable whether this effect is significant for this particular terminal, as most vessels with unresolved laytimes do not require tug assistance (vessel classes smaller than Handymax class vessels). Waiting for pilotage, however, could contribute to the waiting times of the other types of vessels; in total 10, Panamax-class vessels had short-term unresolved waiting times (see Figure 4.10). Waterway congestion is another potential reason for the short-term discrepancy in waiting times.

Third, vessels could have potentially waited during the downtime of the port due to reasons other than tidal restrictions, such as fog, wind, and storms. The significance of this downtime is debatable, as its occurrence is infrequent. Other downtimes may theoretically be caused by daylight and the working hours of the terminal, but this is not a major factor for this terminal, as departures and arrivals occur almost uniformly throughout the day. Less frequent reasons for the long-term discrepancies may include the unavailability of berths due to barges, special operations, and calamities. However, it is believed that seagoing vessels do have priority over barges. Special operations such as lightering operations of large vessels that are otherwise not able to enter the port directly due to draught restrictions, are not applicable for the PoR. Calamities involving vessels that are broken down, and require repairs could have potentially caused additional waiting times, but this is highly unlikely.

Testing alternative maintained bed level designs

Terminal congestion was observed to account for most of the waiting time of the fleet, while tidal windows are less significant for the fleet. This aligns with the port policy that states that 99.0% of the tides should be accessible to any inbound vessel with a draught of 15.0 m. Our model found that the current MBL design of the channel is slightly underdimensioned, with a tidal accessibility of 98.4%.

Applying the validated nautical traffic model to the previous MBL design of the NWW (14.5 m instead of 16.2 m, i.e., a decrease of 1.7 m), it was found that the four deepest-draughted vessels with draughts of 14.8 and 15.0 m could not enter the 3e PET. Furthermore, assuming that the tidal restrictions will now apply to vessels with a draught of 9.3 m (i.e., 11.0 m minus 1.7 m), more inbound trips (9.0% instead of 4.6%) will be subject to these rules. The total waiting time due to tidal restrictions, however, decreases from approximately 21.5 hours to about 19.5 hours. This is because most vessels fall within the lenient window-based current velocity regime. The percentage of vessels prone to the strict point-based current velocity tidal window decreased from 8.3% to 4.2% (with port accessibility for design vessels with draughts of 13.5 m around 99%).

In case the exclusion of the four deepest-draughted vessels is unacceptable, a more moderate reduction of 0.5 m in the MBL of the Nieuwe Waterweg and Scheur could be undertaken. The model found that this results in a degree of accessibility of 59.1% for the design vessel, leading to a 33.6% increase in the total modelled waiting times. This increase consists of 73.4% of waiting time due to the cascading effects of the tidal window; the rest (26.6%) is waiting time directly caused by the tidal restrictions. On the other hand, based on Figure 4.7, more considerable gains in the reduction of the MBL can be obtained by redirecting the deepest-draughted New Panamax and Suezmax class vessels to other deep-sea terminals (i.e., Maasvlakte). The model found that by diverting the 9 deepest-drafted vessels, the desired service level could be achieved with MBLs that are 3.0 m higher than the current MBLs. More vessels will then be prone to a tidal window, however, with an increase in the total waiting time of only 2.7%, with potentially lower dredging costs.

4.5 Discussion

4.5.1 Usability of the results of the quantification method for port improvements

Given that the largest portion of resolved vessel waiting times is due to congestion, it can be confirmed that this process should be included in the mesoscopic agent-based nautical traffic modelling method implemented in the OpenTNSim library. Based on the limited waiting times, it was found that the terminal operates efficiently. Depending on the actual causes of the unresolved waiting time, congestion should be further reduced to improve the terminal's efficiency. As the terminal area is limited, optimisation of land-based and berth planning and occupancy may need to be considered. Therefore, a more in-depth study of the actual causes of the waiting time is recommended. For the port authority, this could help identify bottlenecks due to limitations in port infrastructure, or whether the waiting time can be accepted.

Tidal downtime and cascading effects were to a lesser extent resolved by the quantification method. This is due to the high degree of accessibility for the liquid bulk terminal, given the MBL design and tidal restrictions policy. Therefore, for the deepest-draughted design vessel, the port accessibility is adequate. However, the tidal restriction policy could be further improved by investigating the point-based horizontal tidal restriction which is the main limiting factor. A further deepening of the NWW, based on the current design vessel, is not required. On the contrary, this chapter shows that a less deep NWW is not recommended either, as this would result in significant waiting times for the design vessel and cascading waiting times for other vessels calling at the port.

4

From a fleet perspective, however, the waiting times due to the tidal restrictions are limited. Since only 0.6% of the vessels require the MBL design of the NWW, a significant reduction in the dredging requirements can be achieved by diverting the deepest-draughted vessels to more offshore-located terminals. A further study considering more inland terminals could quantify the feasibility and effects of such an intervention. Special attention should be given to the attractiveness of the port. Shipowners and shipping companies may not remain with the PoR when subjected to tidal restrictions or diversions to other terminals (G. Xiao *et al.*, 2024; Richmond and Casali, 2022). The performance of the quantification method in different scenarios should be tested further, for example by simulating the situation during the shallower NWW before 2019. The quantification of cascading effects due to tidal downtime is necessary for such studies. Hence, although the tidal downtime and subsequent cascading effects were only marginal, including these processes in the quantification method is essential.

4.5.2 Challenges to overcome for further hindcast studies with the quantification method

While the validation of the quantification method implemented through OpenTNSim was successful, the underlying hindcast study was challenging due to the numerous sources of data and the extensiveness and error-proneness of AIS data.

First, the nautical traffic model presented here relies on an extensive set of geospatial, hydrodynamic, and AIS data. In other case studies, these datasets may not be available. The availability of hydrodynamic data, for instance, depends on measurement campaigns and/or numerical models, which may be lacking and are costly to establish. Moreover, AIS data may be restricted or absent (e.g., for new ports or future scenarios). While the availability of these datasets is expected to improve the results significantly, the quantification method can also be used with synthetic data. Further research is needed to confirm this.

Second, although the processing and analysis of AIS data successfully resulted in the required information, the reliance of the nautical traffic model on AIS is not entirely reliable and could have potentially led to errors in the setup and validation of the hindcast simulation with the quantification method. AIS data are known to contain errors in the manual, static (i.e., draught) and dynamic (i.e. Global Positioning System (GPS), SOG) information, which was also observed in this chapter. As severe GPS errors caused idle vessels to drift in space, the method could occasionally not distinguish idle from sailing vessels. These errors have potentially resulted in erroneous laytimes of vessels at the wrong infrastructure. Contributing to this problem was the fact that AIS data were sometimes missing around the berth areas, seemingly caused by the operators of the vessel that forgot to switch on the AIS. These errors could be minimised by removing outliers based on the SOG, but this parameter was also found to have inadequacies. The outlier removal process could not be fully relied upon, and some errors remained. A more extensive analysis should be conducted, as it may be necessary for further studies.

Finally, the mapping of the AIS tracks onto the network has led to errors in vessel speed. Vessels did not always follow the simplified network. This has contributed to errors in the vessel delay estimation in the order of several minutes. Future research may need to address this simplification for cases where such small deviations are considered problematic.

4.5.3 Further improvements to be incorporated in the OpenTNSim library

Although the results from the OpenTNSim-based quantification of the waiting times are promising, significant discrepancies remain between the modelled and observed laytimes of vessels in the anchorage area. The implemented quantification method has several limitations that may need to be addressed in future studies.

First, various port processes have been neglected in this quantification method, which may explain part of the discrepancies and/or may be required in different case studies but were deemed outside the of scope in this chapter. Most prominently, the land-based terminal operations were disregarded (Cartenì and de Luca, 2012; Roy *et al.*, 2023). These are thought to cause significant long-term, cascading waiting times for vessels of several hours to days. Based on expert judgment, cargo is occasionally not ready for handling, often due to delayed handling of preceding vessels or delays in cargo processing at the terminal. Therefore, it is strongly recommended to perform a study involving the development and validation of a fast discrete-event method to simulate terminal operations in conjunction with the nautical traffic.

Second, other omitted processes that could have contributed to resolving more short-term waiting times are waterway congestion due to ambient traffic (Jafari Kang *et al.*, 2022), traffic regulations such as those the Río de la Plata (Frima, 2004), congestion caused by limited tug and pilot availability (Nikghadam, 2023), and downtime due to other external environmental conditions (Camus *et al.*, 2019). These processes may interact with each other, as more adverse weather conditions (i.e., strong winds from particular directions) may lead to higher demand for tugs and pilots, which could exceed their capacity during peak traffic flows. Depending on the specific case, further research into the cascading waiting times due to such processes is recommended.

Third, other neglected processes that affect the speed of vessels, and could have led to delays of several minutes, are vessel encounters and overtaking, vessel properties (e.g., draught), and hydrometeorological conditions (e.g., currents and winds) (Shu *et al.*, 2017). Modelling the correct speed for tide-bound vessels is important to calculate the tidal windows. In this validation chapter, due to the short distances and few tide-bound vessels, these factors would not have significantly affected the results. However, it is recommended that the aforementioned processes be included in further studies.

Lastly, some port infrastructure and traffic management processes were neglected in this chapter. In addition to the land-based operations at terminals, other types of terminals, such as container and dry bulk terminals with quays instead of jetties, were not considered. While jetties have a unit capacity, quay-type terminals also have limited crane or excavator equipment that determines the laytime of vessels at the terminal. Scheduling these cranes based on vessel demand is a port process that should be incorporated into the quantification method in future research. This could be formulated as a fast integrated berth allocation and quay crane assignment problem, as presented by Iris *et al.* (2015). The same holds for the capacity of anchorage areas (J. Zhao *et al.*, 2023), and waterway traffic management (Liu *et al.*, 2021). The inclusion of jetty allocation plans, such as those Sienz and Innocente (2008), in the quantification method is also a subject for further research.

4.5.4 Significance of the method for new applications

Although many further improvements to the quantification method are possible, it can be observed that the data-driven mesoscopic quantification method, implemented through the open-source OpenTNSim library, already yields very promising results. By including realistic hydrodynamics, detailed accessibility policies and berth availability information, the method could rapidly quantify and resolve the fleet's laytime in the anchorage area due to the cascading delays of terminal congestion and tidal restrictions. Furthermore, it was possible to establish a relationship between the degree of accessibility of ports, which for the 3e PET was in accordance with de Jong (2020), and the waiting time of vessels. Therefore, the approach presented in Chapter 3 is considered to be accurate enough to test alternative MBL designs based on the impact of the fleet's waiting time, rather than on the accessibility percentage of a single design vessel. This is a significant advantage over design-vessel approaches. In particular, the quantification of the cascading effects proved to be highly important for this. Although these effects currently have a limited impact on the fleet's waiting time in the current situation, they become increasingly important when the MBL become shallower and more vessels are affected by the tidal restrictions.

It is also worth noting that the open-source library of OpenTNSim offers excellent opportunities for further development of the quantification method, in collaboration with other researchers and stakeholders. The proposed quantification method can be implemented in port and waterway systems worldwide for various purposes. There are ample opportunities to use the method as an operational tool for real-time modelling or nowcasting to optimise short-term planning of port operations. Additionally, the quantification method can serve as a forecasting tool on tactical (medium-term) and strategic (long-term) levels, to test alternative traffic regulations, accessibility policies, vessel-priority rules, waterway and berth layouts, and the effects of changing fleets of vessels on port operations. The application of probabilistic and machine-learning tools on AIS data will be essential to support these applications.

4

4.6 Conclusions

The work in this chapter aimed to validate the proposed quantification method for water transport performance in estuaries, and its implementation in the open-source library of OpenTNSim (Chapter 3). The application of the proposed method, using actual AIS data and matching physical data for the Port of Rotterdam, has shown that the method can explain a significant part of the observed vessel traffic that behaved normally — as in not showing excessive long waiting times that are likely related to issues other than the physical port design. As such, this chapter answered sub-question 3 (SQ 3): *How accurately can the quantification method replicate waterborne transport performance?*

Based on the hindcast modelling of nautical traffic bound for/from a liquid bulk terminal in the 3e PET of the PoR in the open system of the NWW in the RMD, the quantification method implemented through the OpenTNSim library can satisfactorily reproduce vessel waiting times that were observed in AIS data. The simulation's setup requires geospatial data, AIS data, and hydrodynamic data from a numerical model as its input. The input is used to construct a geospatial graph of the port network, resources that schematise the port infrastructure (i.e., terminals, anchorage areas, and turning basins), agents with properties that represent the vessels of call (i.e., arrival times, draughts, laytimes at the terminal and turning basins), and tidal and traffic restrictions, including vessel speeds and realistic hydrodynamics over the graph. The nautical traffic model reproduced 73.4% of the non-excessive vessel laytimes in the anchorage area, modelling 60.7% of the vessels-of-call in accordance with the observations. Decomposition of the causes of the fleet's waiting time results in 98.0% of the observed waiting time being generated by terminal congestion while waiting time due to tidal restrictions is limited to only 2.0% of the observed waiting time. This finding meets the expectations, as the NWW's MBL is designed for the deepest draughted design vessel that comprises 0.6% of the calling fleet. Consequently, a marginal 5.0% of the fleet is prone to tidal restrictions, with 1.2% of the fleet experiencing consequential waiting times. Therefore, the cascading effects of tidal restrictions are limited for this specific case study. However, by running various alternative MBL designs, these cascading effects become important, highlighting the added value of the modelling approach of resolving tidal downtime and congestion for a fleet jointly, rather than for a single design vessel.

Still, a discrepancy of 69.2% is found between the modelled and observed vessel laytimes in the anchorage. Most of this discrepancy is expected not to be related to waiting time caused by the interactions between the fleet, the physical environment, and the wet infrastructure, but is due to land-based terminal operations and other economic considerations. For studies where increased accuracy is required, adding such aspects to the quantification method implementation can likely further improve the simulation results. The open-source and modular structure of the OpenTNSim library makes the addition of such factors feasible. However, another downside can be the required availability of data. Despite these potential improvements, the implemented quantification method's current performance is satisfactory in assessing the impacts of changes to the physical system on waterborne transport performance objectively and transparently.

5

Method application: Trading-off port efficiency and freshwater availability

Nothing is more difficult, and therefore more precious, than to be able to decide.

Napoleon Bonaparte

As highlighted in Chapter 1, socioeconomic developments, climate change, and subsequent human interventions have led to highly pressured estuarine systems in which the set of stakeholder interests can no longer be satisfied simultaneously. This results in complex trade-offs for which policy and decision-making are often reliant on qualitative assessments, which could result in suboptimal designs. To mitigate this situation, Chapters 2 and 3 propose a method to quantify water transport performance as a function of the physical environment. The method was implemented through the open-source library of OpenTNSim. Chapter 4 demonstrates that the proposed method is capable of resolving real observed waiting times, in a case application to the PoR. Now that we have a suitable quantification method, this chapter addresses the following sub-question (SQ 4): **How can the interests of waterborne transport be objectively weighed against other stakeholder interests in more objective policy and decision-making?** To answer this question, this chapter investigates the trade-off between the conflicting stakeholder interests of waterborne transport and freshwater availability during the extremely dry year of 2022 in the RMD. To inform this trade-off, the now-validated simulation-based nautical traffic modelling method — as presented in Chapter 3 — is applied for varying bed levels in the NWW, the open connection to the North Sea, and the main waterway of the PoR. The consequences of the changed bed levels on the hydrodynamics in the system are derived from numerical simulations. The impact of these water system modifications is subsequently translated to water transport performance and drinking water availability. To enable a subsequent trade-off, a general framework of performance indicators is assembled that translates the aforementioned impacts to normalised performance indicators. The framework results in a multi-stakeholder trade-off curve that clearly illustrates how improved freshwater availability competes with port efficiency as a function other than the MBL. This quantified insight into how different stakeholders are affected by the same system intervention directly contributes to the main research question of this thesis. Although the framework can and should be expanded and applied further, and requires stakeholder engagement, it provides a promising first step towards more objective decision-making in estuaries where waterborne transport is a key stakeholder.

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5.1 Introduction

Globally, deltas have been attractors of both human activity and other forms of life. This is because they provide fertile soils, access to freshwater, and an open connection to the sea (Maul and Duedall, 2019; Pont *et al.*, 2002). In addition, estuaries are ecologically valuable systems due to their high biodiversity (Tangelder *et al.*, 2017), and their calm waters function as nurseries (Breine *et al.*, 2011; Tulp *et al.*, 2008).

Due to their attractiveness, estuaries house many different stakeholders with often conflicting interests: (1) communities require fresh surface waters for drinking water, agriculture, and industry, and low water levels for safety (e.g., Temmerman *et al.*, 2013; Wada *et al.*, 2011); (2) waterborne transport demand sufficient water depths and low current velocities to facilitate safe operations for deep-draughted vessels (van Koningsveld *et al.*, 2023); and (3) ecological diversity contributes to estuarine resilience (e.g., Folke *et al.*, 2002; Loreau *et al.*, 2003), which arises from the multitude of gradients generally present in natural estuaries (e.g., Mestdagh *et al.*, 2020; Tangelder *et al.*, 2017; Ysebaert *et al.*, 2003).

Over time, humans have interfered in the estuarine system to optimise performances deemed important: e.g., (1) channel deepening to improve the accessibility and efficiency of port and waterway systems (e.g., Best, 2019; Johnson *et al.*, 1987); (2) closure of estuaries for water safety (e.g., Figueroa *et al.*, 2022; Orton *et al.*, 2023); and (3) the creation of freshwater buffers to ensure freshwater availability (e.g., Morris, 2013; Tönis *et al.*, 2002). However, such large-scale interventions generally have negative side-effects on other estuarine functions not considered in the assessments (e.g., de Vet *et al.*, 2017; van Wesenbeeck *et al.*, 2014; Z. Yang *et al.*, 2010).

With the ongoing urbanisation of estuaries and globalisation worldwide (Maul and Duedall, 2019), conflicting stakeholder interests are becoming more apparent. At the same time, the changing climate is putting additional pressure on the estuarine functions supporting these interests; e.g., leading to reduced freshwater availability (Alcamo *et al.*, 2007; Distefano and Kelly, 2017; Kumar *et al.*, 2013). As a result, decisions and policies must be made regarding more sensitive trade-offs in a crowded, high-stakes environment.

An example of a trade-off between conflicting stakeholder interests is the increasing demand for deeper waterways to limit vessel waiting times — i.e., improve waterborne transport efficiency (Almaz and Altiok, 2012) —, while there is increasing demand for freshwater (Distefano and Kelly, 2017; Vörösmarty *et al.*, 2000). Deeper estuaries are, however, known to cause more salt intrusion (e.g., D. V. Hansen and Rattray Jr., 1965; Veerapaga *et al.*, 2020; Hendrickx *et al.*, 2023b), pressuring freshwater availability. Worldwide, the advantages of economies of scale lead to larger and deeper-draughted vessels, pushing channels to be deepened and ports to be expanded to maintain efficient waterborne transport; e.g., Bahía Blanca, Argentina (Zilio *et al.*, 2013); Hudson River, NY, USA (Ralston and Geyer, 2019); Mekong Delta, Vietnam (Nguyen and Le, 2023); Mississippi River, LA, USA (Johnson *et al.*, 1987); Niger Delta, Nigeria (Dada *et al.*, 2016); Pearl River, China (Yuan and Zhu, 2015); Rhine-Meuse Delta, the Netherlands (Cox *et al.*, 2022b); Yangtze River, China (Q. Chen *et al.*, 2019).

Under normal conditions, such deepened waterways generally do not strain the freshwater availability. However, during droughts, they can cause freshwater shortages. Substantial efforts are made to mitigate the impact of such channel deepening during threatening events: e.g., in the Lower Mississippi River (LA, USA), a temporary earthen sill is placed during droughts to stop the landward propagation of the salt wedge (Fagerburg and Alexander, 1994; Hendrickx *et al.*, 2024; Johnson *et al.*, 1987), which, nevertheless, resulted in severely stressed freshwater reserves (e.g., end of 2023; Miller and Hiatt, 2024); in the RMD (the Netherlands), a costly and complex freshwater distribution network that transports water from upstream to downstream locations to meet the freshwater demands during a drought (HydroLogic, 2015; HydroLogic, 2018).

Both these examples reflect rare, extreme events for the cases of the Mississippi River (Miller and Hiatt, 2024) and the RMD (Toreti *et al.*, 2022; Wegman *et al.*, in review). However, such severe droughts are part of a trend of increasing droughts worldwide (T. Zhao *et al.*, 2024), and are projected to increase in both frequency and duration (Jones *et al.*, 2024; J. Lee *et al.*, 2024). Therefore, the pressure on estuaries and their livability will also increase with climate change as well.

The clear opposing interests of stakeholders pose a challenge for policy and decision-makers. Not only are the impacts of water depth on waterborne transport, accessibility, and freshwater availability highly nonlinear, but the performance metrics also do not align and are difficult to translate into monetary units As a result, policy and decision-makers are forced to compare apples with oranges.

Therefore, this chapter showcases a newly assembled framework that enables policy and decision-makers to quantifiably assess trade-offs between conflicting and dissimilar interests of socioeconomic stakeholders. The framework is applied in the case study of the severely dry year of 2022 in the highly urbanised and intensively utilised RMD. In this estuary, the depth of the main channel was recently deepened to improve waterborne transport performance, but shallowing is now considered an option to improve freshwater availability. The research therefore focuses on quantifying the trade-off between these two major stakeholders, given bed-level change.

This chapter is structured as follows. Section 5.2 provides a detailed overview of the trade-off in the RMD. Section 5.3 describes the materials and methods used to quantify the effects of changing bed levels on the interests of the port and freshwater intakes. Section 5.4 presents the obtained trade-off curve of the performance indicators. Sections 5.5 and 5.6 provide the discussion and conclusions, respectively.

5.2 Case study: Rhine-Meuse Delta

5.2.1 System description

The RMD is the delta of the confluence of the Rhine (Waal and Lek branches) and Meuse rivers (Figure 5.1). This delta consists of multiple branches, with five emissaries, the NWW being the principal outlet under average discharge conditions, and an open connection to the North Sea. The main source of freshwater to the RMD is the snowmelt- and rain-fed Rhine river with an average discharge of 2,160 $m^3\ s^{-1}$, compared to the on average 290 $m^3\ s^{-1}$ contributed by the rain-fed Meuse River (Sperna Weiland *et al.*, 2015).

The magnitude and division of the incoming freshwater across the branches are regulated by weirs and discharge sluices. This is based on the measured water level of the Rhine at Lobith, where the river enters the Netherlands. The multi-objective goal of this water management system is to jointly (1) guarantee water safety, (2) provide and store freshwater, (3) facilitate inland shipping, and (4) protect ecological values (Rijkswaterstaat, 2019).

The NWW is designed to convey 1,500 $m^3 s^{-1}$ to limit salt intrusion. This design discharge is achieved by regulating the Haringvliet Sluices (Rijkswaterstaat, 2019), located at the mouth of the Haringvliet, south of the NWW (HV in Figure 5.1). Together with a mesotidal amplitude of around 1.5 m at the mouth of the NWW, this estuary is classified as a salt-wedge estuary (de Nijs *et al.*, 2011). Under such average conditions, the salt intrusion reaches 24 km inland, near the Botlek harbour (Figure 5.1a; de Nijs *et al.*, 2009).

When the discharge in the Rhine at Lobith drops below 1,700 $m^3\ s^{-1}$, the design discharge of the NWW cannot be maintained causing the saline water to intrude beyond the Botlek far into the Nieuwe Maas (Figure 5.1b). To convey as much freshwater as possible through the NWW during this situation, the Haringvliet Sluices remain almost completely closed (Rijkswaterstaat, 2019). The further the discharge at Lobith drops, the more saltwater intrudes inland. In addition to the hindrance to inland shipping due to the shallow upstream water depths (Vinke *et al.*, 2022; Vinke *et al.*, 2024), freshwater availability along the northern branches of the RMD becomes particularly pressured, as brackish water reaches the mouths of the Hollandsche IJssel and the Lek (Figure 5.1b)— two branches with many water inlets and little discharge, which is exacerbated during droughts (van den Brink *et al.*, 2019; Wegman *et al.*, in review). The upstream end of the Hollandsche IJssel becomes fully brackish within a few days due to ongoing water extractions (van Zaanen *et al.*, 2022).

Most recently, extreme drought events occurred in 2018 and 2022 in the RMD (Toreti *et al.*, 2019; Toreti *et al.*, 2022; Wegman *et al.*, in review). During these droughts, the discharge at Lobith remained below 1000 $m^3\ s^{-1}$— with a minimum of 679 $m^3\ s^{-1}$ in 2022— for roughly 4 and 2 consecutive months in 2018 and 2022, respectively, causing significant damage (Rijkswaterstaat, 2023; Vinke *et al.*, 2022; Wegman *et al.*, in review).

5.2.2 Port of Rotterdam

The PoR is located in the RMD, which is the largest port in Europe. It is a major stakeholder in the delta with significant regional and (inter)national interests. The port serves as the gateway

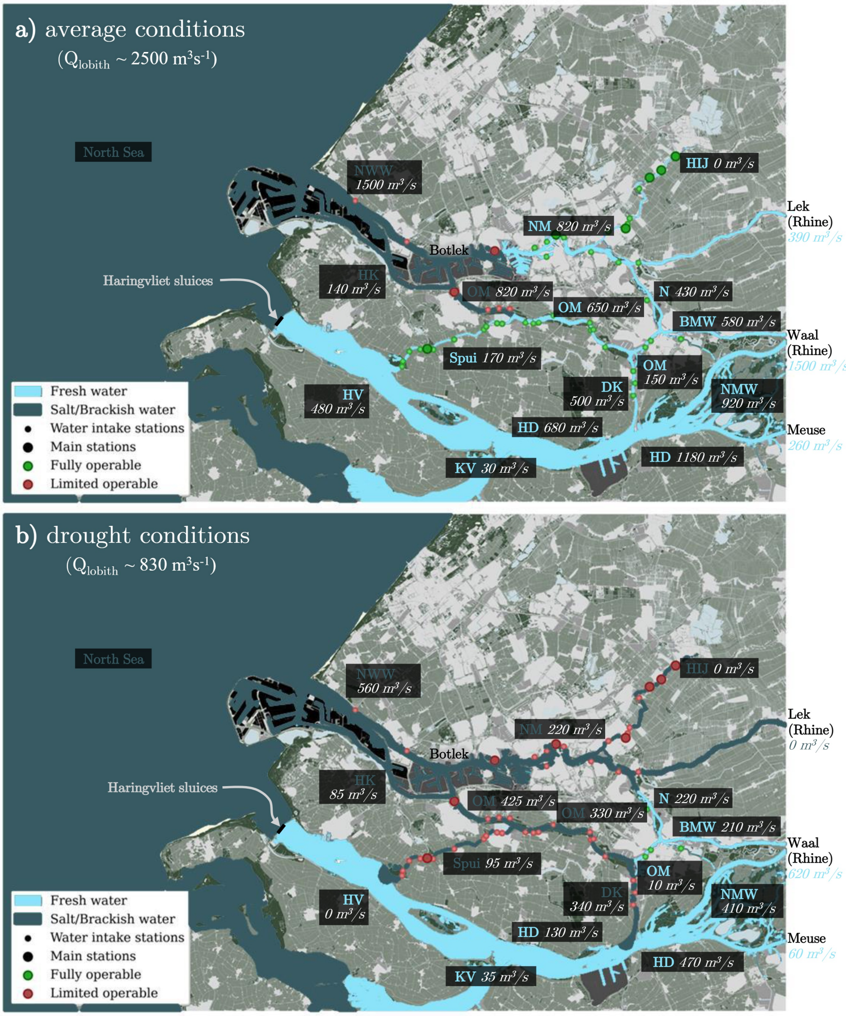

Figure 5.1: Overview of the RMD highlighting the branches it is made, including their discharge and the brackish water extent during average conditions **(a)** and during a drought **(b)**. The water intake stations that are affected by the brackish water are highlighted. **BMW**: Beneden Merwede; **DK**: Dordtsche Kil; **HD**: Holllands Diep; **HIJ**: Hollandse IJssel; **HK**: Hartel Kanaal; **HV**: Haringvliet; **N**: Noord; **NM**: Nieuwe Maas; **NMW**: Nieuwe Merwede; **NWW**: Nieuwe Waterweg; **OM**: Oude Maas; **VK**: Volkerak-Krammer. Discharges and salt intrusion based on volume balances of de Vries (2014), van der Wijk (2016), and HydroLogic (2019b). Note that actual discharges may change due to local water extractions or discharges, which are not included. This mainly occurs in summer, when local precipitation no longer meets the freshwater demand. Other countermeasures to limit saltwater intrusion, such as flushing discharges in the Lek and HIJ, are also not included, leading to exaggerated saltwater intrusion extents in these branches in the figure

5

of many types of cargo and products through intermodal transport to North-Western and Central Europe. In 2022, the PoR transshipped 467.4 million tonnes of cargo (Port of Rotterdam, 2024).

The PoR can roughly be subdivided into a deepwater/offshore part, and a shallower, inland part (Figure 5.1). The inland harbour basins are connected to the sea through the open connection of the NWW and Scheur, which are hereafter jointly referred to as NWW. The bed levels of the port basins and waterways are maintained through dredging according to an MBL design (Figure 5.2). This design facilitates the access of the deepest-draughted vessels in each specific port basin's fleet.

In the port, vessels are subject to tidal restrictions depending on their characteristics: draught, length, type, destination, etc. Vertical tidal restrictions involve regulations for minimum UKC with respect to the MBL. These result in water level thresholds. Moreover, horizontal tidal restrictions prescribe specific current velocities and set limits on exceeding them. These restrictions interact with the congestion of port infrastructure— i.e., terminals, turning basins, waterways, and anchorage areas—, leading to delays in cargo transfers (see Chapters 3 and 4).

In 2019, the NWW was deepened from 14.5 to 16.2 m to accommodate seagoing vessels of the New Panamax class with a maximum draught of 15.0 m. Following the NWW, the Nieuwe Maas has a MBL of 14.5 m decreasing to a minimum of 11.5 m that is used by seagoing (cruise) vessels to moor in Rotterdam (near intake station 4 in Figure 5.2). Further details on the PoR and its nautical logistics can be found in Chapter 4.

Figure 5.2: Overview of the land-based and water-based functions in the RMD, including the design of maintained bed levels of the Port of Rotterdam and the water intake stations. Labelled water boards: **(A)** Hollandse Delta; **(B)** Delfland; **(C)** Schieland & Krimpernerwaard; and **(D)** Rijnland. The numbered water intake stations correspond with Table 5.1. The water intake station labelled with a * represents the water intake stations upstream of the Hollandsche IJssel (5, 6, and 7). The lowercase, Roman numerals represent locations of data validation presented in Figure 5.4: (i) Spijkenisseburg, (ii) Krimpen a/d IJssel, and (iii) Kinderdijk.

5.2.3 Freshwater users

Water management in the Netherlands is regulated by water boards, four of which are located in the RMD (Figure 5.2): (A) Hollandse Delta; (B) Delfland; (C) Schieland & Krimpenerwaard; and

(D) Rijnland. These four water boards are responsible for approximately 4 million people (Unie van Waterschappen, 2022), and require freshwater to fulfil three main requirements (Klijn *et al.*, 2012): (1) minimum and maximum water levels, (2) water quality, and (3) water quantity for consumption, such as drinking water and irrigation.

The water boards have several water intake locations throughout the RMD, shown in Figure 5.2. These predominantly consist of pumping stations that remove excess water from the polders to the river system during wet conditions, and vice versa during dry conditions. In addition, the water boards redistribute water amongst themselves using pumping stations, creating alternative routes for the freshwater. These are currently only used during severe droughts when the brackish water reaches some of the upstream water intake stations (Figure 5.1b; van der Heijden *et al.*, 2024).

Note that the demand for freshwater increases during droughts, in particular for irrigation. A precipitation deficit of around 0.225 m can result in a shortage of freshwater for the stakeholders. A further deficit can lead to insufficient water levels and flushing capacity (Klijn *et al.*, 2012). This occurred in 2018 and 2022 when the water boards had to make heavily rely on the alternative freshwater supply routes (Hesen, 2021; van der Heijden *et al.*, 2024). However, the operation of these systems causes damage to the canal system due to increased water levels and current velocities (HydroLogic, 2018). Improvements to the systems have been made to increase its capacity at a cost of millions of euros. These improvements led to fewer problems during the 2022 drought (van der Heijden *et al.*, 2024).

5.2.4 Future challenges

Freshwater availability in the RMD is expected to become further pressured due to recent climatological and socioeconomic developments. These developments involve (1) reduced freshwater supply due to more frequent and severe low discharge events in the Rhine (Buitink *et al.*, 2023; Sperna Weiland *et al.*, 2015) and increased upstream water usage (Klijn *et al.*, 2012); (2) increased salt intrusion due to the lower discharges in the NWW and the rising offshore water levels due to sea level rise (van Alphen *et al.*, 2022); and (3) higher freshwater demands due to more frequent and longer droughts, and increased flushing discharge requirements to combat salinisation of the groundwater (Klijn *et al.*, 2012).

Although the current water management solutions are claimed to be a robust system (HydroLogic, 2019a), they may become inadequate with these developments. Extracting more freshwater from upstream to facilitate the downstream needs, causes reversed discharges in the Hollandse IJssel and Lek branches, exposing them to further salinisation; a problem that arose during the droughts of 2018 and 2022 (Figure 5.1b; HydroLogic, 2019b; Wegman *et al.*, in review). As a result, freshwater was redirected from the major rivers to flush these branches, which, in turn, caused further hindrance to inland shipping activities (HydroLogic, 2019b; Vinke *et al.*, 2022; Vinke *et al.*, 2024). Moreover, the operation of this system leads to damage to the water boards, and further extensive investments that are required to increase the capacity of the solution may not be cost-effective. In addition, this approach further pressures other estuarine systems that depend on the same upstream discharge such as the North Sea Canal and Lake IJssel (Hendriks and Mens, 2024). Thus, not all stakeholder interests can be satisfied during a drought in the RMD in its current state.

5.3 Materials and methods

To assess the effect of bed level change in intensively-utilised estuaries, it is essential to quantify the implications for the affected stakeholders. Therefore, a general framework is assembled that enables evaluating dissimilar stakeholder interests (Figure 5.3). Once a problem has been identified—generally raised by one or more stakeholders—, the following four steps set up the multidisciplinary trade-off framework:

1. Select a minimal set of design parameters that quantify the main properties of the area of interest or measure.

2. Determine stakeholders that are affected by this set of design parameters and define a single performance indicator per stakeholder that reflects their performance.

3. Define quantification methods that translate the environmental conditions to the performance indicators.

4. Select quantification methods — or a pipeline of quantification methods — that are able to reflect the environmental conditions based on the set of design parameters.

After setting up models for each of the quantification methods, the performance indicators can be calculated. By varying the design parameter, the framework can evaluate the trade-off between the two stakeholder interests, using multi-objective (Pareto) optimisation.

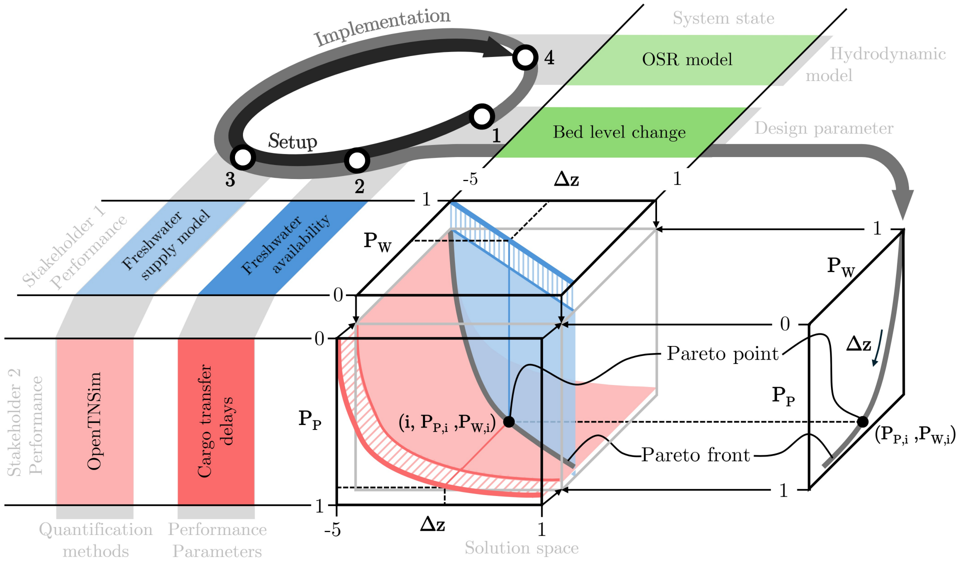

Figure 5.3: The conceptual model of the trade-off framework of dissimilar stakeholder interests. A design parameter (i.e., bed level change) feeds into a hydrodynamic model (i.e., *OSR model*) which output is used in models that calculate the stakeholder performance indicators (i.e., cargo transfer delays for the port and availability for the freshwater supply), ranging from 0 (worst) to 1 (best). Thus, a certain system state, i, results in a so-called Pareto point of the two indicators. By changing the design parameter along a certain range (i.e., -5 to 1 m of bed level change), a Pareto front can be constructed using the Pareto points. This front can be flattened to a relation between the two performance indicators. Note that the implementation of the method follows the reverse order of the above-described method setup.

In this chapter, the above framework is applied to the RMD during the severely dry year of 2022. For this, the MBL is selected as the design parameter, represented as bed level change, Δz. A positive value (i.e., $\Delta z > 0$) indicates an increase in MBL— i.e., deeper water depth— and vice versa. To assess the impact of bed level change on environmental conditions, a hydrodynamic model of the RMD is used that could determine the effects of bed level change on the local hydrodynamics (Section 5.3.1). Its output data is then utilised in models that quantify the effects of hydrodynamic changes on cargo delays (Section 5.3.2) and freshwater availability (Section 5.3.3). Finally, these effects are translated into performance indicators, which allowed for the construction of a Pareto front to provide insights into the relevant trade-off between the stakeholder interests (Section 5.3.4).

5.3.1 Hydrodynamic model and scenarios

To quantify the stakeholder interests outlined in Sections 5.3.2 and 5.3.3, data on water levels, flow velocities, and salinity are required throughout the RMD domain. To simulate the effects of changing the MBL on the hydrodynamics and salt intrusion, a coarser version of the OSR model is used. The OSR model is run operationally to provide information for the pilots in the PoR and is well-calibrated for water levels and current velocities (Kranenburg *et al.*, 2015). The hydrodynamic model is used to hindcast the year 2022, which experienced a severe drought (Toreti *et al.*, 2022; Wegman *et al.*, in review). Such conditions play a key role in the design and performance of the freshwater supply system.

Although not the main objective of the model, salinity predictions are satisfactory ($R^2 = 0.9073$; Figure 5.4a), with the largest errors occurring at higher salinity levels (Figure 5.4b). With the focus on breaching a threshold value ($s_c = 150\ mg\ Cl^-\ l^{-1}$), the key question is whether the model correctly predicts exceedance, which it does for 91.1% of the time (Figure 5.4a); if incorrect, the model generally underpredicts the salinity— i.e., it predicts a higher freshwater availability.

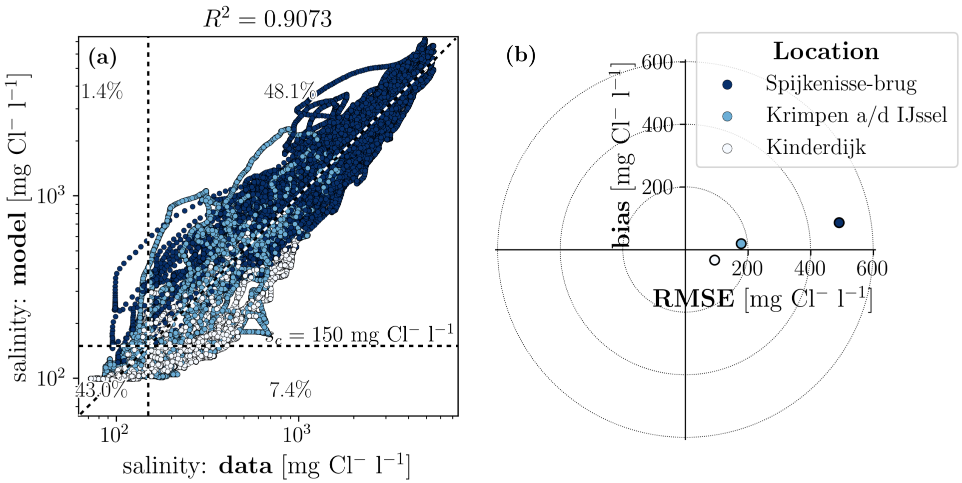

Figure 5.4: Predictive power of hydrodynamic model regarding salinity. **(a)** Measurements versus predictions with the salinity threshold (s_c =150 mg Cl⁻ l⁻¹) marked with a black, dashed line; and **(b)** target plot displaying the root-mean-squared-error (RMSE) and bias. Locations are shown in Figure 5.2: (i) Spijkenisse-brug, (ii) Krimpen a/d IJssel, and (iii) Kinderdijk.

The reference model run simulates the MBL of the NWW as the existing situation (16.2 m; $\Delta z = \pm 0.0$ m). Based on the distribution of draughts of vessels that navigate the NWW, a total of five shallowed MBL designs were created ranging from 11.2 m ($\Delta z = -5.0$ m) to 15.2 m ($\Delta z = -1.0$ m), with steps of 1.0 m. Shallower MBL designs were not considered, as they were expected to result in an unreasonably poor port performance. Additionally to these runs, a scenario involving a 1.0 m deepening to an MBL of 17.2 m was assessed to examine the effect of a further deepening ($\Delta z = +1.0$ m).

5.3.2 Quantifying cargo transfer delays

Waterborne transport relies principally on its efficiency and throughput. An efficient port means that cascading waiting times for cargo transfers due to downtime and congestion of port infrastructure should be limited (see Chapter 2). Shallower MBLs can increase these waiting times, since more vessels will be more constrained by tighter tidal windows, reducing the port's accessibility (see Chapter 4). Moreover, shallower bed levels can decrease the throughput to the inland port, as the deepest-draughted vessels in the fleet may no longer be able to navigate the access channel. If these vessels are redirected to more offshore terminals, this can further decrease the port's efficiency due to the congestion of these terminals.

To quantify the effects of bed-level change on this parameter, a nautical traffic model based on the mesoscopic agent-based simulation model using the OpenTNSim library (similar to the software publication of Bakker *et al.* (2024)) was deployed. This agent-based discrete-event method estimates the cascading waiting times of vessels due to the interaction between tidal downtime and berth congestion. To set up such a model for the RMD, three main features are configured based on an analysis of hindcast AIS data for the year 2022, hydrodynamic model results, and geospatial data: (1) the PoR's wet infrastructure; (2) vessels of call, including their properties, such as draught, laytimes and speed; and (3) tidal hydrodynamics, namely water levels and current velocities. The tidal restriction regulations are taken from the port authority's policy. For simplicity, the nautical traffic model includes only a selection of terminals in harbour basins connected to the North Sea through the NWW. Hence, indirect effects on other terminals are not taken into account. Based on the AIS data analysis, 12 terminals have been selected over different harbour basins. These terminals are prone to tidal restrictions that are impacted by bed level change that affects at least 20 vessels of call. More details on the data preparation and processing, as well as the model setup, can be found in Chapter 4, along with the underlying software of a similar model, published in Bakker *et al.* (2024).

As the shallower bed levels are expected to fully restrict the passage of the deepest-draughted vessel through the NWW, the cargo throughput to the inland terminals may drop. It is assumed such a drop in throughput is unacceptable for the port, and therefore this throughput will be maintained in the nautical traffic model using replacement coasters. Arriving vessels with excess draughts are assumed to be redirected to a feeder terminal in the offshore port. At the feeder terminal, these vessels will be lightered, and the excess cargo will be transferred to and transshipped by coasters with equivalent transport capacity to reach the inland terminal. Additionally, departing vessels with excess draughts will be loaded with their excess cargo at the offshore feeder terminal. Also here, this cargo is then transshipped by coasters from the inland terminal.

5.3.3 Quantifying freshwater availability

The interest of the inhabitants of a delta— or surrounding an estuary— is reflected by freshwater availability. Therefore, the water intake stations in the delta are crucial in providing this commodity to them. Water intakes can only extract water from the river system if salinity levels are below a certain threshold; in the Netherlands, this threshold is 150 mg $Cl^- \, l^{-1}$ (or 0.27 psu). Furthermore, water intakes often rely on gravity to extract water; i.e., the water level in the river system must exceed a critical threshold, which is generally around the mean water level— this is generally around the mean water level. Therefore, water extraction (i.e., freshwater supply) only occurs if the following two criteria are met:

$$\eta(t) > \eta_c \tag{5.1a}$$

$$s(t) < s_c \tag{5.1b}$$

where η is the water level in the river system [m]; η_c the water level threshold of the water intake [m]; s the salinity in the river system [psu]; and s_c the salinity threshold of the water intake [psu].

Both the supply and demand of freshwater fluctuate on different time scales: daily, seasonally, etc. Therefore, water intake locations— or collections of water intakes— generally have some form of storage capacity. These storage volumes follow a basic volume balance:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = E(\eta, s) - D(t) \tag{5.2}$$

where E is the supply of freshwater [$m^3 s^{-1}$], which is a function of the water and salinity levels (Equation 5.4); and D the demand for freshwater [$m^3 s^{-1}$].

The storage volume is bounded by a minimum volume of zero— i.e., $V = 0$— and by a maximum capacity:

$$0 \leq V \leq V_c \tag{5.3}$$

where V_c is the storage capacity associated with the (collection of) water intake(s) [m^3] (Table 5.1).

The supply of freshwater in Equation 5.2 is a binary relation depending on Equations 5.1a and 5.1b:

$$E = \begin{cases} E_{\max} & \text{if Equations 5.1a \& 5.1b} \\ 0 & \text{else} \end{cases} \tag{5.4}$$

where $E_{\max}$ is the maximum extraction rate of the water intake [m^{3}s^{-1}] (Table 5.1).

Water shortages occur when demand exceeds the supply (or extraction rate) and storage is empty. It is defined as the demand that cannot be met by the combination of water supply and reserves:

$$S = \begin{cases} D - E - \max\left\{-\dfrac{\mathrm{d}V}{\mathrm{d}t}; 0\right\} & \text{if } V < D - E \\ 0 & \text{else} \end{cases} \tag{5.5}$$

where D is the freshwater demand of the (collection of) water intake(s) [m^{3}s^{-1}] (Table 5.1); E the extraction rate [m^{3}s^{-1}] (Equation 5.4); and V the stored freshwater volume of the (collection of) water intake(s) [m^3]. The last term (i.e., the $\max$-function) reflects the use of the remainder of stored freshwater— if any.

To apply the above metric to the situation in the RMD, the main water intakes and their collections are selected based on van der Wijk (2020), which are presented in Table 5.1. Since the hydrodynamic model poorly predicted salinity in the Hollandsche IJssel, the main water intakes in this branch— marked with asterisks in Table 5.1— were evaluated based on the modelled hydrodynamic data at Krimpen aan de IJssel (Figure 5.2). Additionally, Gemaal Winsemius and Inlaat Bernisse used the same hydrodynamic data, as they respectively take in and redistribute water from the same source; and Krimpenerwaard was projected on hydrodynamic data at the mouth of the Lek, as the model domain of the OSR does not include the upper Lek branch — i.e., at Kinderdijk (marked with † in Figure 5.2).

Table 5.1: Specifications of the main water intakes in the Rhine-Meuse Delta without emergency water supply (derived from van der Wijk, 2020), as more detailed data was lacking. The numbering of the water intakes reflects the locations numbered in Figure 5.2. Numbers post-fixed with an asterisk are collectively considered at Krimpen aan de IJssel, marked by an asterisk in Figure 5.2. V_c: storage capacity; D: freshwater demand; $E_{\max}$: maximum extraction rate.

	Water board	**Intake station**		V_c [m^3]	D [m^{3}s^{-1}]	$E_{\max}$ [m^{3}s^{-1}]
A.	Hollandse Delta	1 2	Inlaatsluis Spijkenisse Inlaatsluis Bernisse	4,000,000	9.1	23.0 23.0
B.	Delfland	(2) 3	Gemaal Winsemius Schiegemaal	492,000	2.75	4.0 3.0
C.	Schieland & Krimpenerwaard	4 5*	Mr. U.G. Schilthuis Snelle Sluis & Gemaal Abraham Kroes	528,000	2.5	4.5 3.3
		6* †	Gemaal Verdoold Krimpenerwaard	3,408,000	5.6	1.5 5.6
D.	Rijnland	7*	Gouda	2,086,400	12.0	21.0

5.3.4 Performance indicators

Using the processing methods, as described in Sections 5.3.2 and 5.3.3, performance indicators are defined that reflect waterborne transport efficiency and freshwater availability. For the port, cargo delays are used, where a perfect port performance ($\mathcal{P}_p = 1$) would be achieved when there are no delays in cargo transfer, i.e., vessel waiting times are zero:

$$\mathcal{P}_p = 1 - \frac{\sum_i^N V_{c,i} T_{w,i}}{\sum_i^N V_{c,i} T_{t,i}} \tag{5.6}$$

where N is the number of vessels entering the port during the period of interest [–]; $V_{c,i}$ the cargo volume of the vessel i [m^3]; $T_{w,i}$ the waiting time of the vessel i [s]; and $T_{t,i}$ the transfer time of the cargo of the vessel i [s]. Note that $\mathcal{P}_p$ is bounded by zero and thus cannot become negative: $\mathcal{P}_p \in [0, 1]$.

The transfer time of a vessel's cargo refers to the total time it would take for a vessel to unload its cargo after arriving at the port or departing at a previous terminal, or to load new cargo before departing the port or arriving at the next terminal. This includes additional waiting time.

The performance indicator for freshwater availability reflects the extent of freshwater shortage. A perfect performance ($\mathcal{P}_w = 1$) is achieved when the water board can meet the freshwater demands at any time. Therefore, this performance indicator is a function of the freshwater shortage relative to demand, integrated over the period of interest:

$$\mathcal{P}_w = 1 - \frac{\int_T S \, \mathrm{d}t}{\int_T D \, \mathrm{d}t} \tag{5.7}$$

where T is the period of interest [s]; S the freshwater shortage (Equation 5.5) [m^{3}s^{-1}]; and D the freshwater demand [m^{3}s^{-1}]. Note that $\mathcal{P}_w$ is also bounded by zero due to which it cannot become negative: $\mathcal{P}_w \in [0, 1]$.

These two performance indicators can be evaluated using a trade-off framework (Figure 5.3). This trade-off is assessed through multi-objective optimisation, which generates Pareto optimal solutions (e.g., Emmerich and Deutz, 2018). This produces a set of solutions that cannot be further improved upon (e.g., Deb, 2001); a so-called *a posteriori* method to inform decision-makers about the optimal alternatives without making *a priori* choices (Miettinen, 1998). Note that this approach results in a collection of optimal solutions, not a single "optimal solution." Here, "optimal" refers to the best trade-off between the chosen performance indicators, which is at best as good as the indicators themselves.

5.4 Results

5.4.1 Delayed throughput

The AIS data analysis revealed that 90.8% of the vessel voyages calling at the selected terminals are not affected by a shallower NWW of 11.5 m (Figure 5.5a). However, because larger, deeper-draughted vessels carry more cargo, it is found that 22.9% of the cargo will have to be transferred to the replacement coasters. The shallower the NWW, the more deeper-draughted vessels are impeded from navigating this channel, and the more trips with replacement vessels have to be made.

The nautical traffic model predicts that the inland part of the PoR is highly affected by a shallower NWW (Figure 5.5b): the average cargo delivery time as the NWW becomes shallower. This is mainly due to the additional delay of transferring cargo onto the replacement coasters, which becomes more pronounced with shallower MBLs. As a result, the average ratio between the delay and delivery time of cargo increases. In addition, extra congestion occurs as more vessels are needed to transship the same amount of cargo. Delays from tidal restrictions also increase, as more vessels are affected by tidal windows due to shallower depths. However, this effect is marginal (Figure 5.5b).

Furthermore, it can be observed that a deeper NWW does not significantly improve port operations for the current fleet of call. Although tidal restriction delays slightly decrease, the port still experiences berth congestion.

5.4.2 Water shortages

The freshwater supply model predicts that freshwater availability, in general, increases with shallower MBLs (see Figure 5.6). The shallower MBLs mean that sudden drops in the discharge of the NWW have less direct consequences on freshwater availability. This is because the OSR model

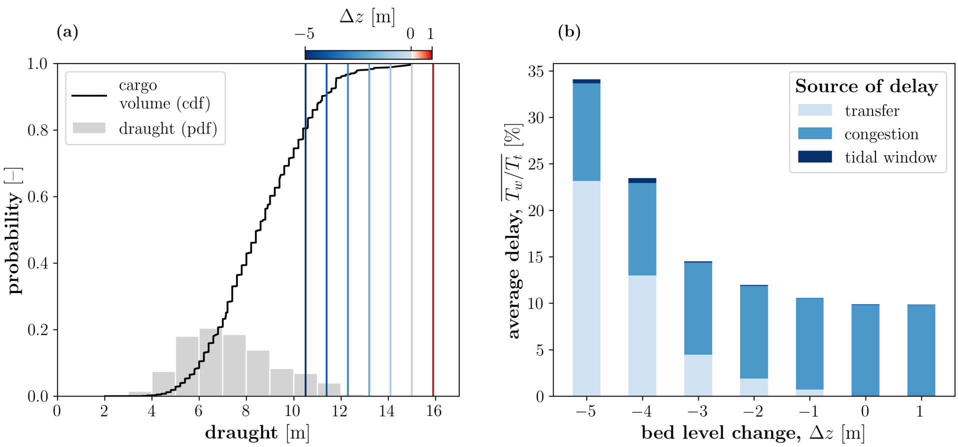

Figure 5.5: Input and output of the nautical traffic model: **(a)** vessel draught and cargo volume distributions based on AIS data. Vertical, coloured lines represent the maximum allowable draught for each bed level change as considered in this chapter. These are based on the PoR's accessibility policy. Note that vessels with a draught greater than 12.0 m exist in the modelled fleet of call, with draughts up to 15.0 m. However, they undertake less than 1.0% of the total voyages and are therefore not clearly visible in the pdf; **(b)** contribution of the delay time to the total delivery time. Transfer delays are caused by transferring cargo between vessels; congestion results from unavailable berths; and delays due to tidal windows relate to the MBL level change.

predicts that a smaller minimum freshwater discharge is required to flush the intruded saltwater (see Figure 5.6a and b). As a result, the freshwater storage in the water boards is larger at the start of periods of low discharge, which postpones and reduces the effects of the drought on the water intake stations.

Freshwater supply to the Delfland and Hollandse Delta water boards is the least susceptible to droughts (see Figure 5.6c and d) despite being closest to the sea (Figure 5.2). The influence of reducing the MBL is, therefore, also least pronounced in these water boards. This is related to the source of freshwater extraction: the Delfland and Hollandse Delta water boards mainly extract from the man-made freshwater lake in the southern RMD— the Haringvliet and the connected Brielse Meer— which are more resilient to droughts (Figure 5.1), but less resilient to storm surges. The other two water boards (i.e., Schieland & Krimpenerwaard and Rijnland) are more reliant on freshwater from the northern RMD, which is more strongly affected by droughts and changes in the water depth of the NWW (see Figure 5.6e and f). In contrast, further deepening the NWW— i.e., $\Delta z = +1.0\ m$— barely affects the freshwater availability with respect to the reference case— i.e., $\Delta z = \pm 0.0\ m$. It is only at the Schieland & Krimpernerwaard water board where a minor difference is visible (Figure 5.6d).

5.4.3 Pareto front

All water boards experience a decline in freshwater availability performance with increasing MBL (Figure 5.7), although the freshwater availability of the Delfland and Hollandse Delta water boards is barely impacted. This aligns with the limited shortages observed during the drought in these water boards (Figure 5.6b and c). Thus with deeper waters, or increased MBLs, comes a poorer freshwater performance, $\mathcal{P}_w$ (Figure 5.7). An exception occurs with deepening of the NWW compared to the reference case; there is a negligible difference between $\Delta z = \pm 0.0\ m$ and $\Delta z = +1.0\ m$.

On the other hand, port performance improves with a deeper NWW. The added value of deep-

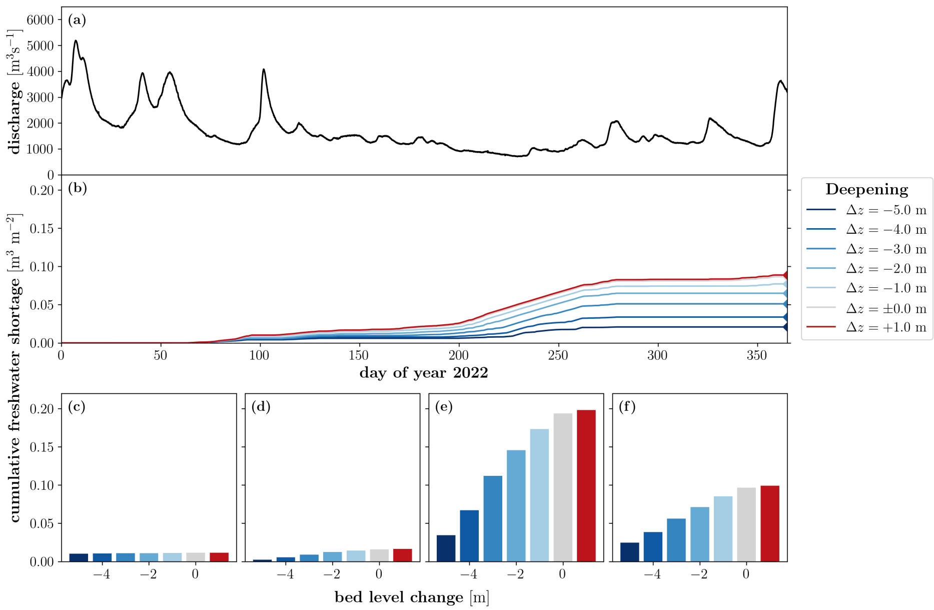

Figure 5.6: The influence of the MBL on the water shortages expressed in rainfall deficits. **(a)** Discharge at Lobith; **(b)** temporal development of cumulative water shortages for all water boards; and cumulative water shortages per water board: **(c)** Delfland, **(d)** Hollandse Delta, **(e)** Schieland & Krimpenerwaard, and **(f)** Rijnland. Shortages are expressed as cumulative lack of freshwater (i.e., volume; time-integration of S, Equation 5.5) per area of the water board. Note that the shortages are expressed in volume per area, which causes the total shortage across all four water boards to be less than the sum of the individual shortages for each.

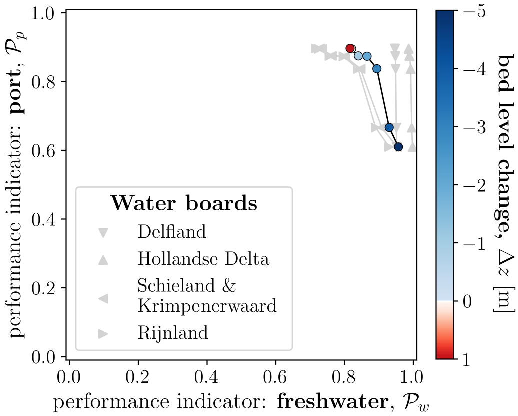

Figure 5.7: Pareto-front of performance indicators as a function of the water depth. The collective is coloured with the water depth, and individual water boards are presented in grey.

ening the NWW on the port performance is, given the current fleet composition, limited beyond an MBL of 16.2 m. This aligns with the expectations based on the current fleet composition in Figure 5.5a, which shows that fewer vessels are impacted with increasing values of MBL.

5.5 Discussion

The MBL in the NWW has a significant impact on both performance indicators, although the sensitivity of the freshwater availability differs across water boards (Figure 5.7). The resulting Pareto front is illustrative but depends on the implemented assumptions in the models (Section 5.5.1). In addition to these assumptions, this section addresses two matters: (1) drought countermeasures other than shallowing (Section 5.5.2); and (2) value-based transformation of the Pareto front (Section 5.5.3).

5.5.1 Model assumptions

As is typical, the choice of quantification methods influences the results— in this case the shape of the Pareto front. First, this chapter has implemented the hydrodynamic model that is used for port operations, where its main objective is the prediction of water levels and flow velocities. Nevertheless, the model shows a good predictive power regarding the salinity (Figure 5.4). However, in smaller branches of the RMD its predictive power regarding salinity decreases. Therefore, a more accurate hydrodynamic model could improve the predictive power in branches like the Hollandse IJssel, where multiple water intakes are located (Figure 5.2; e.g., Geraeds *et al.*, in prep. Gerritsma *et al.*, in review, describe detailed hydrodynamic models focused on salt dynamics in the RMD). However, note that the implementation of a more detailed model incurs higher computational costs.

Second, the nautical traffic model heavily relies on AIS data as input. Although generally of good quality, vessel laytimes and speeds were impacted by frequent location errors. These had to be detected and manually corrected, a procedure that likely influenced the magnitude of the cargo transfer delays. The same applies to the assumption that the cargo throughput to the inland terminal is maintained by smaller replacement vessels, as well as the selection of replacement vessel type. Furthermore, OpenTNSim neglects tugs, pilots, background traffic, and terminal cargo flows (see Chapter 4), which influences the nautical traffic behaviour. Regarding the port performance indicator (Equation 5.6), there is a significant dependency on the cargo volumes that were calculated from the vessel dimensions in the AIS data. As vessel dimensions in the AIS data are known to be susceptible to errors and uncertainties (Meyers *et al.*, 2022) — especially draughts, which had to be manually corrected for — the volume-based weighting of the waiting and transfer times, and hence the performance indicator itself, includes errors. Additionally, the required number of replacement vessels may be overestimated. Despite all these assumptions and possible errors, it is believed that the state-of-the-art mesoscopic agent-based nautical traffic model, based on the open-source OpenTNSim library, performed as intended, and the resulting levels of port performance are trustworthy. However, further improvements to the quality of the AIS data, the nautical traffic model and its underlying modules, and formulation of the waterborne transport performance indicator are possible and preferable.

Freshwater availability and its related performance indicator — i.e., Equation 5.7 — heavily rely on the hydrodynamic model predictions of water levels and salinity. Furthermore, the use of a basic freshwater balance has its limitations, such as the constant freshwater demand, a single salinity threshold, and exclusion of precipitation input. Despite these simplifications, the results align with experienced shortages (van der Wiel *et al.*, 2021).

In this chapter, the performance indicators were defined according to our best understanding of the problem. For example, it was hypothesised that port performance could be assessed through cargo delays — i.e., port efficiency — would best represent the port's interest. This performance indicator is most relevant to the operability of the port infrastructure, given its interactions with the nautical traffic and physical environment. However, other performance indicators could have been used depending on the stakeholder interests, such as performance indicators based on cargo throughput, nautical safety, or vessel emissions. The same applies to freshwater shortage, which focuses more on the instantaneous effects of the drought and less on cumulative effects. The presented trade-off framework is, however, flexible to support other sets of performance indicators. Note that the performance indicators implemented are metrics and, as such, inherently incomplete.

However, non-monetary metrics were intentionally used to reflect the stakeholders' interests as closely as possible.

Finally, the trade-off was only investigated for the severely dry year 2022, as it was considered the most relevant year for freshwater availability. A different (wet) period or simulation duration could have led to different results and may require differently formulated performance indicators.

5.5.2 Drought countermeasures

The simulated year of 2022 contained a severe drought resulting in an "extremely rare low flow" in the Rhine, particularly during August (Toreti *et al.*, 2022; Wegman *et al.*, in review). Although it is observed that shallower bed levels can significantly improve the resilience of freshwater availability, an MBL of 11.2 m would not even be sufficient to protect all water boards in the RMD from water shortages during such a severe drought ($\Delta z = -5.0$ m in Figure 5.6). Thus additional measures to ensure drinking water safety are required, even when the NWW would be shallower (i.e., MBL $= 11.5$ m). In other words, while effective, shallowing alone cannot ensure freshwater availability in a densely populated delta like the RMD.

Currently, a crisis plan with an alternative water supply system is already in place in the Netherlands to cope with extreme drought conditions by relocating freshwater between water boards — a plan that was also implemented during the 2022 drought (van der Heijden *et al.*, 2024). As mentioned in section 5.2, this relocation plan was not implemented in this chapter, as it is a crisis plan that comes with significant costs (HydroLogic, 2018).

In addition to, or instead of, such a crisis plan, more robust and permanent measures could be implemented. Regarding freshwater availability, four components can alleviate pressure during droughts: (1) increase the freshwater storage capacity (V_c); (2) increase the maximum extraction rate ($E_{\max}$); (3) reduce the freshwater demand (D); and/or (4) move water intakes away from salt-sensitive regions. Note that these components should not be considered in isolation but can be combined to create a resilient freshwater management system.

The last component is also what makes the Delfland and Hollandse Delta water boards relatively insensitive to the MBL of the NWW: these water boards extract the majority of their freshwater from the southern RMD, namely the man-made, freshwater lake Haringvliet. Current plans to reconnect the Haringvliet with the North Sea by (partially) opening the Haringvliet sluices (Brevé *et al.*, 2019; Reeze *et al.*, 2022) could lead to increased salinisation (Kranenburg *et al.*, 2023) and should therefore be carefully assessed (Hendrickx *et al.*, in prep.).

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5.5.3 Performance valuation

The Pareto front in Figure 5.7 clearly shows the trade-off between the port and freshwater performances arising from modifying the MBL. On average — i.e., for all water boards collectively —, the port performance is more affected by the depth of the NWW than the freshwater performance, as shown by the angle of the Pareto front and the range of the values covered.

Given a Pareto front, the mathematically optimal solution can be achieved by maximising the square area below the Pareto front (e.g., Emmerich and Deutz, 2018); this square is bounded by the origin and the Pareto front, i.e., $(\mathcal{P}_w, \mathcal{P}_p)$. However, the Pareto front presented in Figure 5.7 does not include the valuation of the solution space. This valuation is subjective and part of the policy and decision-making process. The valuation of each performance indicator is generally nonlinear and can put limits on the allowable performance values. To maintain the intuitive visualisation of the Pareto front, the valuation can be included using valuation functions:

$$\mathcal{V}_i(\vec{x}) = v_i(\mathcal{P}_i) \cdot \mathcal{P}_i(\vec{x}) \tag{5.8}$$

where $\mathcal{V}_i$ is the valued performance indicator i [–]; v_i the valuation function of performance indicator i [–]; $\mathcal{P}_i$ the (unvalued) performance indicator i [–]; and $\vec{x}$ the design parameter(s).

The transformation of the Pareto front as shown in Figure 5.7, due to arbitrary valuation functions is presented in Figure 5.8. Note that these valuation functions are arbitrarily defined and serve as examples of how they transform the Pareto front. A minimum performance can be enforced by setting a very low valuation for performances below this minimum. For example, in Figure 5.8, the port performance is required to be $\mathcal{P}_p \geq 0.6$ (approximately).

Although the valuation functions in Figure 5.8 are smooth, tipping points that are relevant to stakeholders can be reflected by discontinuities. Since the definition of such a valuation function is

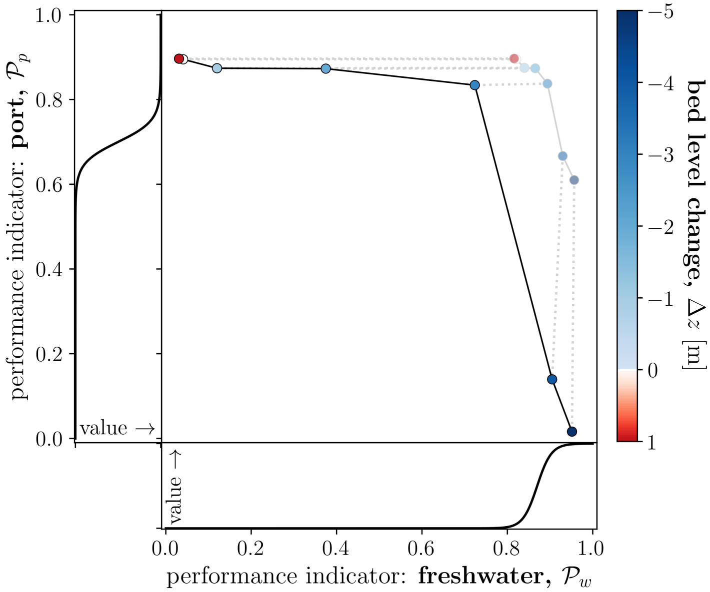

Figure 5.8: Valued Pareto front based on arbitrary valuation functions. The unvalued Pareto front is faded and presents the same data as in Figure 5.7. The valued Pareto front follows from the transformation of this unvalued front with the valuation functions on the left and bottom of the figure using Equation 5.8.

subjective, political, and influenced by the zeitgeist, solely example valuation functions are included in Figure 5.8. This chapter refers to Greco *et al.* (2016) and Keeney and Raiffa (1993), for example, to define such functions, which are intended to reflect stakeholder interests. Note that the function may depend on the period of interest and simulation time.

Figures 5.7 and 5.8 illustrate how insightful and intuitive the use of Pareto fronts is in policy and decision-making; they clearly show the trade-offs associated with the decisions and policies at stake. These features also make such visualisations useful in communicating the policy and decision-making process to the public, who are generally not experts in the field but are highly affected by the decisions and policies being made. This is particularly useful in digital twins (Wannasin *et al.*, 2024), integrated assessment models (Pourteimouri *et al.*, 2024), and serious games (den Haan *et al.*, 2020; den Haan *et al.*, 2024).

Although this chapter was limited to two performance indicators and one design parameter, the presented approach — i.e., the use of design parameters, performance indicators, and a Pareto front — can easily be upscaled to multiple dimensions (e.g., Emmerich and Deutz, 2018). Note that with increasing dimensionality, visualising the trade-offs may become harder due to the human visual limit of three dimensions. Moreover, the construction of the complex multidimensional Pareto front requires many Pareto points, and hence lots of model simulations. Therefore, an effective sampling method — e.g., an adaptive sampling approach — could be used to limit the number of (costly) model simulations (Gramacy and H. K. H. Lee, 2009; Hendrickx *et al.*, 2023a). Additionally, computationally efficient hydrodynamic and stakeholder models can be employed, which may sacrifice precision and resolution. For example, in this research, the idealised and simplified saltwater intrusion model of Biemond *et al.* (2024a) could become useful or fast predictions of the freshwater availability performance.

Finally, this chapter highlights the general applicability and usefulness of the trade-off framework in other case studies. An example is the decision to partially open the Haringvliet sluices in which freshwater availability and ecology have to be weighed against each other (Section 5.5.2; Hendrickx *et al.*, in prep.). Other examples may include the future design and management of the highly urbanised and strongly pressured RMD and other worldwide deltas. For this system in particular, it is anticipated that the presented system-scale and objective approach will be a highly effective tool for policy and decision-makers in identifying the most effective solutions to the most urgent challenges.

5.6 Conclusions

Since the mesoscopic agent-based quantification method for water transport performance (Chapter 3) was shown to give sufficiently accurate results in a real-world validation case (Chapter 4), this chapter addresses sub-question 4:: *How can the interests of waterborne transport be objectively weighed against other stakeholder interests in more objective policy and decision-making?*

In conclusion, a generally applicable framework can be applied that translates changes to the physical system into quantitative trade-off curves between the impacts on the stakeholders' KPIs. These curves can include a KPI for waterborne transport, which can be calculated using the proposed method based on the open-source OpenTNSim library. The framework was used in this chapter to explore the socioeconomic implications of MBL change in the NWW, considering the severely dry year of 2022. Thereby, the trade-off of the dissimilar, conflicting interests of the two major stakeholders in the area was assessed: (1) the Port of Rotterdam, and (2) the collection of water boards extracting freshwater from the delta. The framework required carefully selected objective, non-monetary KPIs to quantify the trade-off using Pareto optimisation. These indicators were calculated based on two separate stakeholder models, namely a validated nautical traffic model and a volume balance model for freshwater supply. The models used the output of a hydrodynamic model of the RMD, and other operational data, such as AIS data and main freshwater intake locations. By varying the MBL of the NWW, the performances of the stakeholders were obtained. The Pareto front illustrates how port performance and freshwater availability compete as a function of changing MBL (Fig. 5.7).

This chapter showed that the resulting Pareto fronts provide valuable insights into the trade-offs of interventions in any multidisciplinary setting. Although the multidisciplinary assessment was limited to two stakeholders, this approach can easily be extended to multiple dimensions— i.e., additional stakeholders with multiple objectives. The Pareto front provides a visually intuitive representation of showcasing the benefits and costs of various scenarios for different stakeholders. By applying valuation functions, the Pareto front can be adjusted to represent performance values, preserving the intuitive visual representation of Pareto fronts (Fig. 5.8). These characteristics make Pareto fronts valuable tools for policy and decision-makers, and public communication. Hence, it is now possible to evaluate the interests of waterborne transport with other stakeholders' interests, leading to more objective policy and decision-making.

6

Conclusions and recommendations

This dissertation addressed the observation that in numerous highly urbanised deltas, worldwide, conflicting stakeholder interests have resulted in highly pressured systems. This set of interests depends on specific estuarine services and functions that can no longer always be fully satisfied. This is especially the case for the often opposing stakeholder interests of waterborne transport and freshwater supply. Due to various socioeconomic developments, larger and deeper-draughted vessels are navigating through deltas to call at seaports. Therefore, deep estuarine channels and larger lock complexes are required which can exacerbate saltwater intrusion and, hence, reduce freshwater availability during droughts. In closed systems, the frequent navigation lock operations during droughts can even result in low water levels and saltwater intrusion to which operational limitations may be required, severely impacting waterborne transport performance. While this leads to complex policy and decision-making, policy and decision-makers rarely quantify the impact of changes to physical systems on the stakeholders' performance, including waterborne transport; the assessments are often limited to quantitative impacts based on hydrodynamic stresses for stakeholders, quantified using non-holistic, simplified model simulations. This presents a major challenge to objective and transparent policy and decision-making.

While the decisions taken are not necessarily wrong, the inability to quantify waterborne transport performance as a function of the physical system state can lead to suboptimal designs that intend to improve waterborne transport performance, but adversely affect other functions or even lead to suboptimal results for the water transport function itself. This can lead to an underestimation of the impacts of projects on stakeholders, particularly those farther away in the estuarine system. It can also result in impracticable mitigation measures — i.e., water management solutions that require more upstream freshwater to limit supply deficits, while it is not studied whether this water would be available. Although extensive EIAs are performed to study the feasibility of deepening and lock expansion projects, they suffer from the above gaps, leading to subjective, suboptimal, and non-transparent decision-making.

Therefore, the main objective of this dissertation was to assemble an assessment method that can objectively quantify the impact of natural and man-made changes on the interests of waterborne transport, aiming to aid policy and decision-making in estuaries where waterborne transport is a major stakeholder. To achieve this, the following research question was considered: *To what extent can the interests of waterborne transport performance be incorporated into more objective policy and decision-making?* Hereby, this dissertation particularly focused on seagoing traffic in estuaries, although its findings are not limited to this scope.

To answer this question, this dissertation applied the following two-step approach. First, a method was established, enhanced, and validated that could quantify the impact of changes to the estuarine system on waterborne transport performance by resolving the key processes. Second, a framework was assembled that could quantify the multi-stakeholder impact of an intervention in the estuary through a trade-off between the impacts on the stakeholders' KPIs, including waterborne transport, estimated with the validated quantification method from the first step. These steps involved the following actions:

1. A literature review was conducted to obtain (1) the main interests of waterborne transport through KPIs, (2) the key interactions between waterborne transport and the physical sys-

tem, and (3) the suitability of existing quantification methods to include and quantify these indicators and processes (see Chapter 2);

2. The most suitable quantification method was selected and further developed to enable assessing (1) the interaction between the waterborne transport system and the physical system, and (2) the impact of changes in the estuary on the performance of the waterborne transport system (see Chapter 3);

3. The enhanced quantification method was validated based on real-world data (see Chapter 4); and

4. The validated quantification method was applied in an objective decision-making approach to a real-world multi-stakeholder case (see Chapter 5).

For the validation and application, the case study of the RMD was adopted, focusing on the open system of the NWW, which forms the gateway to the inland terminals of the PoR. This estuary was deemed representative of many estuaries worldwide. Therefore, the methods and findings, presented in this dissertation can be generalised to other estuaries. Moreover, the methods can be generally applied to trade-offs between other stakeholder interests — e.g., water safety, ecology, and socio-cultural well-being (see Section 6.2).

In this chapter, Section 6.1 presents the main conclusions to the sub-research questions that were defined in Chapter 1. Based on these findings an overall conclusion to the main research question is formulated. Section 6.2 discusses the main implications of this research in a wider context. Subsequently, Section 6.3 presents recommendations for further research.

6.1 Main conclusions

The work reported in this dissertation leads to the following conclusions for the sub-questions that were formulated in Chapter 1.

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6.1.1 How effectively can existing methods assess the waterborne transport performance by quantifying its underlying interactions with the physical system?

Although various quantification methods exist that can assess the performance of waterborne transport, no openly available quantification method was found to be able to accurately quantify the impacts of changes in the physical estuarine environment on nautical traffic performance. For this, a method should quantify vessel waiting times, which was found to be the most important KPI for waterborne transport performance from a nautical viewpoint. Moreover, congestion and tidal downtime should be simultaneously resolved by the method, as these processes can cause cascading vessel waiting times. Tidal downtime results from the economically optimised MBLs of the narrow estuarine channels, which are only navigable by the deepest-draughted vessels during high and calm water. It was found that this forms the main interaction between nautical traffic and the physical environment in open estuarine systems, as the underlying restrictions are based on minimum water depth and maximum current velocity. In addition, in closed systems, quantification methods should resolve vessel delays at navigation locks in relation to the saltwater intrusion fluxes and freshwater losses that are caused by navigation lock operations. This requires an estimation of the door-open and levelling times of individual lock operations.

It was found that existing quantification methods do not resolve these processes simultaneously. While some port accessibility tools optimise the MBLs of waterways based on the tidal requirements of the deepest-draughted vessels, they lack the quantification of cascading waiting times for fleets of vessels. In contrast, microscopic methods can quantify vessel waiting times due to congestion of specific port and waterway infrastructure and services but are too computationally expensive to model the interactions of the larger nautical traffic system in estuaries. Since macroscopic methods are rarely found in the literature, the most appropriate type of quantification method was found to be the mesoscopic method. Such methods can simultaneously model large study areas while being able to resolve more detailed local processes. However, none of the open available mesoscopic methods had yet simultaneously included the properties that are required to model cascading vessel waiting times — i.e., realistic hydrodynamics, vessels of call, accessibility policies, lock operations, vessel-priority rules, and detailed berth availability.

Based on a systematic comparison of available approaches, the quantification method to model nautical traffic behaviour based on the open-source, Python-based OpenTNSim library was deemed the most suitable mesoscopic model. This agent-based discrete-event method can simulate the navigation of vessels (agents) over an extensive network of waterways, schematised as a graph of nodes and edges. Its architecture, which allows new features to be added to the library in the form of so-called mix-in classes, makes it an excellent platform for including the integration of the aforementioned missing processes.

6.1.2 How can the most suitable quantification method be enhanced to more extensively include the interactions between waterborne transport and the physical system?

Since the OpenTNSim library consists of modules that entail mixins to schematise vessels and waterway infrastructure, additional modules can be added based on both existing and new mixins. However, this implementation of a mesoscopic agent-based quantification method for simulating seagoing traffic in estuaries lacked detailed modules to account for tidal downtime and congestion of port infrastructure. The method required a more detailed schematisation of terminal layouts. Additionally, the interactions between the waterway network and hydrodynamics were insufficiently represented. Furthermore, the existing Locking module also lacked details, as it could not estimate vessel delays in relation to saltwater intrusion fluxes and freshwater losses in closed systems. Therefore, new algorithms needed to be developed and incorporated into the library.

Ultimately, a Seaport module was developed, and the Locking module was enhanced. The Seaport module includes detailed port infrastructure — i.e., the physical layout of terminals, anchorage areas, and turning basins — and the interactions between vessels and these infrastructures, including tidal downtime. The infrastructural components were added to the graph to represent the entire capacity-limited port and waterway system. A 'VesselTrafficService' mixin was included, which acts as a Vessel Traffic Services, communicating in advance with vessels about tidal windows and the availability of port and waterway infrastructure. Thus, vessels wait at the destined anchorage areas, instead of entering the port during too shallow water depths, exceeding critical currents, or unavailable infrastructure. The mixin calculates waiting times based on tidal policies that can be added to the graph — i.e., tidal restrictions, MBLs, and speed limits. These policies are enforced based on hydrodynamic data that is provided to the Vessel Traffic Services — e.g., based on output from numerical modelling methods. The Locking module was enhanced to accurately resolve door-open times, levelling times, and vessel delays around lock complexes in closed systems. For this, the Locking module was expanded to include waiting areas, line-up areas and chambers. Complex algorithms act as a Lock Master and Operator, managing vessel interactions. The output of the lock module can serve as input for a semi-empirical lock exchange modelling method — i.e., the Zeesluisformulering (Weiler *et al.*, 2019) — to quantify saltwater intrusion fluxes and freshwater losses. These can serve as boundary conditions for numerical modelling methods to quantify far-field saltwater intrusion in a closed system.

6.1.3 How accurately can the quantification method replicate waterborne transport performance?

Given the enhancements to OpenTNSim, application of the quantification method to a hindcast study of nautical traffic to a specific inland sea terminal in the PoR replicated more than 70% of the observed non-excessive waiting times in AIS data. The method's success lies in its ability to incorporate derived input data from real-world AIS data, hydrodynamic data from a validated numerical model, and geospatial data of port and waterway infrastructure.

Cascading waiting times, however, were only marginally observed in the post-deepened main waterway of the PoR, the NWW, which forms an open connection to the sea in the RMD. This is explained by the deep MBLs of waterways, which have been optimised based on the deepest-draughted design vessels, and the infrequent calls of these vessels; only 4 vessels with a design draught of 15.0 m were found in the AIS data of 2019. Only 2 occurrences were found in the AIS data of 2022. Consequently, less than 5% of the vessels calling at the port are prone to tidal windows, of which less than 25% are predicted to experience waiting time due to these tidal

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restrictions. Although one might argue that the hypothesis of jointly modelling congestion and downtime is false, scenarios involving shallower MBLs showed that cascading effects do indeed emerge.

Therefore, based on the validation results, there is high confidence that the implemented quantification method can accurately assess the impact of changes to the physical system on waterborne transport performance by resolving the interactions between waterborne transport and the physical system.

6.1.4 How can the interests of waterborne transport be objectively weighed against other stakeholder interests in more objective policy and decision-making?

To objectively evaluate stakeholder interests, this dissertation assembled a generally applicable framework to construct trade-off curves of (non-monetary) KPIs reflecting different stakeholders' interests, including waterborne transport. The performance of the latter can be quantified using a mesoscopic agent-based nautical traffic modelling method, as implemented through the OpenTNSim library. The applicability of this framework was demonstrated by an application that quantified the trade-off of bed level changes in the NWW between the waterborne transport performance in the PoR on the one hand, and freshwater users in the RMD on the other. The resulting trade-off curves provide a visual and intuitive representation of dissimilar and conflicting stakeholder interests, that can serve as input into estuarine policy and decision-making.

The first step in the framework's functioning is to establish a quantitative design parameter that characterises the proposed design — i.e., *bed level change*. The next step is to identify other stakeholder interests that are affected by changes to this aspect of the physical environment — i.e., *the nautical traffic system and freshwater users*. For each of these performance metrics, indicators were designed to represent these stakeholders' interests: *cargo transfer delays and freshwater availability*. Key to the proposed method is that the performance metrics per user function are non-monetary and represent the degree of satisfaction of the stakeholder interest, bounded between 0 (0%) and 1 (100%) — i.e., the *degree of cargo transfer delays of the cargo delivery time*, and the *degree of satisfied freshwater demand*. The quantification of these performance metrics could subsequently be done through simulations — i.e., *the proposed nautical traffic modelling method for port efficiency* and a *volume balance for freshwater supply*. To generate the desired trade-off information, each performance metric must be explicitly linked to quantifiable physical properties of the estuarine environment — i.e., *water depths and current velocities in the nautical traffic model*, and *water levels and salinity in the volume balance*.

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Once the trade-off problem is defined, the final step is to quantify the performance metrics through simulation of the physical system's behaviour — i.e., a *hydrodynamic model of the RMD*. Now, by varying the design parameter that was defined in the first step, it is possible to quantify the performance response of each of the stakeholder interests that was defined in the subsequent steps. Calculating the performance response for each stakeholder interest for a range of design parameter values, allows us to construct multi-dimensional trade-off curves. These trade-off curves that strictly quantify the function performance response can subsequently be fed into the policy and decision-making process. The final step to aid the decision-making process is to add stakeholder assessment profiles to each of the user functions. Each assessment profile specifies what function loss is considered acceptable and what level of function loss is considered unacceptable. Although the specification of assessment profiles per user function is subjective, it does reveal how one stakeholder's opinion affects the interests of others. This should facilitate discussions between stakeholders. Note that the valued stakeholder performance curves do not necessarily have equal intrinsic values, since non-monetary units are used. Therefore, they do not lead to a clear economic optimum; this is where the decision-maker comes into play.

6.1.5 Final statement

In conclusion, this dissertation demonstrated that, despite earlier shortcomings, it is now possible to objectively represent the interests of waterborne transport in policy and decision-making. To achieve this, the mesoscopic agent-based nautical traffic modelling method, implemented through the OpenTNSim library, enables the quantification of non-monetary KPIs related to the waterborne transport performance, linking the interactions between the nautical traffic system and the physical system. Thus, alterations to this physical system to improve waterborne transport performance can be thoroughly validated. Moreover, by similarly quantifying the non-monetary KPIs of other stakeholder interests affected by changes to the physical system, intuitive trade-off curves between disparate and conflicting stakeholder interests can be constructed. This enables objective and transparent policy and decision-making in complex systems with multi-objective stakeholder interests.

6.2 Main implications

In a broader context, this dissertation has led to some key implications, regarding the quantification of waterborne transport as a function of the physical system, as well as the use of this quantification method in multi-stakeholder trade-off discussions.

6.2.1 OpenTNSim: a library to assess system-scale impacts on nautical traffic

This dissertation has demonstrated that the state-of-the-art quantification method adopted, from the open-source and Python-based OpenTNSim library, can be used to quantify the impacts of anthropogenic interventions and climate change on nautical traffic systems.

Although this research has only considered the open branch of the RMD, the quantification method's functionality allows for equal applications to other open systems — e.g., the Scheldt Estuary, Mekong Delta, Hudson and Delaware River Estuaries, Chesapeake Bay, Yangtze River, Pearl River, and many more. Moreover, for closed systems, the method can assess the effectiveness of new lock complex designs and corresponding countermeasures to limit freshwater losses, such as in the case of the Panama Canal (Calvo Gobbetti and Ríos Córdoba, 2024), and saltwater intrusion fluxes, such as at IJmuiden (PoA) (Hendriks and Mens, 2024) and Canal Ghent-Terneuzen (Scheldecommissie, 2023). The library can also be used to study other nautical traffic systems, such as inland waterway systems and offshore TSSs, including anchorage areas.

While this dissertation specifically focused on the interaction between tidal downtime and infrastructure congestion the proposed quantification method can be used to study other processes. For example, it can be implemented to assess traffic regulations related to encountering and overtaking in the Río de la Plata (Frima, 2004), or tug and pilot availability in the PoR and PoA (Nikghadam, 2023). Moreover, the quantification method can be used to study the impact of downtime — e.g. wind and wave conditions, visibility, and working hours. To address this, the library should be expanded with new mixins, including these processes and corresponding realistic physical information, such as waves, wind, fog and day-and-night cycles — e.g., based on hydrodynamic and meteorological modelling methods. This is possible as the library is modular.

Lastly, the proposed method can quantify the impacts on other multi-objective KPIs of waterborne transport — e.g., vessel emissions (M. Jiang *et al.*, 2023; van der Werff *et al.*, 2024b; van der Werff *et al.*, in rev.) and nautical safety (van der Werff *et al.*, 2024a; van der Werff *et al.*, in rev.). Therefore, there is confidence that the method can be of significant aid in the policy and decision-making process in areas worldwide where waterborne transport is a major stakeholder.

6.2.2 A framework for objectively trading-off stakeholder interests

This dissertation also led to a framework that enables the objective construction of trade-off curves between conflicting and dissimilar stakeholder interests. These curves are intuitive and are anticipated to support rational and transparent policy and decision-makers by objectively evaluating stakeholder interests.

The framework is not limited to this dissertation's application of quantifying the bed level change in the NWW of the PoR and freshwater users in the RMD. The framework is ready to be used in other trade-offs that are not related to nautical traffic, such as those between the interests of water safety, ecology and socio-cultural well-being — i.e., the framework has been used in (Brunink and Hendrickx, 2024). Moreover, in a broader context, it is envisaged that the framework can be applied to other water bodies — e.g., coasts, rivers, lakes — and even in non-hydrodynamics-related areas — e.g., in land use and sustainability challenges.

Although the results of this application have not yet been used in practice, it is anticipated that the port and water boards will be able to cooperate through this framework, which was not always possible in the past. Further stakeholder engagement is required for this. Therefore, the intuitive trade-off curves are expected to be used in digital twins (Pourteimouri *et al.*, 2024) and serious games (den Haan *et al.*, 2024), which are effective tools for providing information to end-users and facilitating communication with stakeholders.

6.3 Recommendations

The very promising results presented in this dissertation give rise to the following recommendations for further research.

6.3.1 Enhancing mesoscopic agent-based nautical traffic modelling methods

In this dissertation, the mesoscopic agent-based nautical traffic modelling method, implemented through the OpenTNSim library, was used to quantify the impact of natural and man-made physical system changes on waterborne transport performance. Hereby, the cascading effects through tidal downtime and infrastructure congestion were considered. Despite these processes, it is recommended that a mesoscopic method should consider the following:

- **Incorporate additional physical factors that affect downtime:**
  The application range of the approach presented here could be extended by including downtime due to wind, waves, visibility, traffic rules, and other physical disruptions (e.g., oil spills, accidents). In some nautical traffic systems, these factors may prevail over tidal downtime

- **Incorporate additional potential sources of congestion:**
  The approach could be further extended by including other known factors that contribute to port congestion, such as tugs and pilot availability, the arrival of inland barges at seaport terminals, and land-based terminal processes (including working hours). Complex interactions between these processes and (tidal) downtime are expected — e.g., the increase in peak demand for tug and pilot assistance during high water, when more vessels are subject to vertical tidal windows.

- **Improve data integration:**
  In this dissertation, primarily geospatial data, AIS data, and hydrodynamic data from a hydrodynamic model were used as input for the nautical traffic model for the PoR. As each data source has its limitations — particularly the error sensitivity of the AIS data (see Chapter 4) — other data sources need to be considered. Examples include meteorological data for wind, the HaMIS[1] data for accurate vessel information, and data on resource management and cargo flows from the terminals. These could be used to further enhance the validity of the quantification methods.

- **Optimise runtime:**
  Especially for larger systems with many vessels and complex processes, the runtime of quantification methods can increase substantially. Currently, the simulations are run on a single laptop. More complex simulations will require running the method on computational clusters to handle larger datasets and improve efficiency.

- **Continue open-source development:**
  For this dissertation, the quantification method was developed using the open-source development OpenTNSim library. Its architecture supports the development of mixin modules that can easily be integrated, meaning that the work of one research can typically be (re)used by others. To be able to capture increasingly complex estuaries, as well as other physical systems, it is recommended to follow a programmatic approach, as proposed by the OpenTNSim library. Here, each new development becomes part of a larger repository of mixins, rather than the more common project approach, where each development becomes a stand-alone method that cannot easily be integrated.

[1] https://www.portofrotterdam.com/nl/eropuit/futureland/de-digitale-haven/slimmere-scheepvaartafhandeling

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- **Increase uptake by lowering the learning curve:**
The OpenTNSim library is open-source and invites wider participation and uptake. However, as a consequence, the library now contains a range of functionalities, of which the learning curve can be quite steep, posing a significant challenge for further use. To facilitate others to use the proposed approaches, and if possible add new approaches themselves, it would be beneficial to invest time in lowering the learning curve. This can be achieved through improved documentation, simplified example applications, and education.

6.3.2 Expanding the multi-stakeholder trade-off framework

Regarding methods that evaluate conflicting and dissimilar stakeholder interests, such as the trade-off framework in this dissertation, the following recommendations are made:

- **Include additional stakeholder interests:**
The multi-stakeholder framework was now applied to two opposing stakeholder interests, namely port performance and freshwater availability. The approach itself can easily be extended to more than two stakeholders. There are many additional stakeholders in estuarine systems where water transport plays an important role, whose interest can be linked to the physical properties of the system. These can relate to water quality parameters — e.g., temperature (for cooling water intake and ecology), and suspended matter (for dredging and ecology) — or water quantity parameters — e.g., water levels (for flood safety), and discharge (for inland waterway transport capacity). It is recommended to test the framework with multiple decision parameters and stakeholder performance indicators.

- **Further reduce bias and subjectivity**:
Inherently, the trade-off framework is susceptible to bias and sensitivity due to the models used and the defined performance indicators. Therefore, further research is recommended to address these issues through sensitivity and/or probabilistic analyses.

- **Construct valuation functions based on stakeholder inputs:**
In line with the previous recommendation, it is critical to value the impacts on stakeholder performance, as this step includes subjectivity. The method discussed in Chapter 5 shows that stakeholder valuation functions can be overlaid on the objective impact, to derive how stakeholder perceptions of the severity of the impacts affect the trade-off optimum. As a next step, it is important to engage actual stakeholder inputs and translate these to valuation functions (see methods of Keeney and Raiffa (1993) and Greco *et al.* (2016)).

- **Consider large timescales:**
The time dependency of the framework should be addressed in further studies, as performance indicators, impacts, and valuation functions, can vary over different periods. For example, the performance of the freshwater supply system is likely unaffected during a wet year, since the most critical conditions for this stakeholder occur during a dry period.

- **Consider larger system scales:**
The approach described in this dissertation was now applied to an open branch of the RMD. The quantification method can handle much larger system scales. An interesting avenue for further research is to extend the quantification method to cover a larger part of the network. In this way, trade-offs can be analysed both between stakeholders in the same part of the system and between those in different parts. An interesting example of this could be to set up a model that includes both the open branch of the RMD at the NWW and the closed branch at IJmuiden, The examples in Chapter 1 showed that water distribution decisions to combat salt intrusion at the IJmuiden locks can also affect the freshwater availability in the RMD at the NWW. To date, such system-scale trade-offs have not been made. The methods presented here make this trade-off in principle feasible.

6.3.3 Further applications

At last, the following recommendations for further research are made for the combined method to quantify waterborne transport performance within the trade-off framework:

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- **Application in the Rhine-Meuse Delta:**
  The methods can be used to assess future plans in the RMD, such as the opening of the Haringvliet Gates and the closure of the NWW by navigation locks. Moreover, past EIAs can be reassessed to reconsider previously executed adaptive interventions, such as the deepening of the NWW. In particular, the methods should be applied in closed systems to verify the Locking module.

- **Application to other estuaries worldwide:**
  There are many systems worldwide where climate change-related changes in the water system affect multiple stakeholder interests. As a final recommendation, it is proposed to apply the methods presented here to other river deltas and estuaries, such as the Scheldt Estuary, the Mekong Delta, Río de la Plata, the Hudson and Delaware River Estuaries, and the Panama Canal.

The above recommendations aim to enhance the accuracy, usability, and applicability of the methods discussed, ultimately improving policy and decision-making in estuarine environments.

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Nomenclature

3e PET 3e Petroleumhaven. 33, 44–48, 50, 52, 53, 55, 57, 62, 65

AIS Automatic Identification System. 21, 34, 39, 43, 44, 46–51, 54–58, 60, 63–65, 77, 79, 80, 82, 85, 89, 92

EIA Environmental Impact Assessment. 4–7, 9, 10, 87, 94

FWA Fresh Water Allowance. 17, 34, 45, 47, 53

KPI Key Performance Indicator. 10, 13, 14, 18, 23, 24, 27, 34, 39, 40, 43, 85, 87, 88, 90, 91

MBL Maintained Bed Level. 13, 15–17, 19, 27, 28, 30, 34, 39, 40, 43–45, 47, 52–54, 58, 62, 63, 65, 69, 73, 75, 76, 79–83, 85, 88–90

NWW Nieuwe Waterweg. 4, 6, 14, 33, 44, 45, 54–56, 58, 59, 62, 63, 65, 69, 71, 73, 74, 76, 77, 79, 80, 82, 83, 85, 88–91, 93, 94

OSR Operationeel Stromings model Rotterdam. 47, 76, 78, 79

PoA Port of Amsterdam. 5, 9, 22, 91

PoR Port of Rotterdam. 4–6, 10, 11, 20, 22, 33, 44, 45, 47, 48, 52, 61–63, 65, 69, 71, 73, 76, 77, 79, 80, 88–92

RMD Rhine-Meuse Delta. 4–6, 65, 69–78, 80, 82, 83, 85, 88–91, 93, 94

TSS Traffic Separation System. 44, 45, 47, 49, 51, 52, 91

UKC Under-keel clearance. 15–17, 19, 20, 30, 34, 45, 46, 48, 52, 53, 59, 73

Epilogue

Through this research, I have gained a deeper appreciation for the complex interplay between hydraulic engineering solutions and societal needs. It is my hope that this work will inspire future researchers to explore innovative approaches to hydraulic engineering, always keeping the ultimate goal of improving human well-being and environmental sustainability in mind rather than the means of a hydraulic model. In this dissertation, we observed that quantifying the system-scale impacts of hydraulic designs on stakeholders' interests is critical for this. While including details can be interesting, and can also be impactful on a system scale, I learnt that it is the system that mandates what level of detail is required. By embracing a systems-thinking approach and prioritizing stakeholder engagement, we can create more sustainable and resilient water systems for generations to come.

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Journal articles

2. F. P. Bakker, G. G. Hendrickx, L. M. Keyzer, S. R. Iglesias, S. G. J. Aarninkhof, and M. van Koningsveld (in review). "Trading off dissimilar stakeholder interests: Changing the bed level of the main shipping channel of the Rhine-Meuse Delta while considering freshwater availability." In: *Environmental Challenges*. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4967335

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Software

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Lecture Notes

1. H. J. Verheij, A. J. van der Hout, O. C. Koedijk, F. P. Bakker, M. van Koningsveld, and H. J. de Vriend (2021). "Part III – Chapter 3 Waterway Elements". In: *Ports and Waterways – Navigating the changing world*. Ed. by M. van Koningsveld, H. J. Verheij, P. Taneja, and H. de Vriend. Delft, the Netherlands: TU Delft Open Publishing. ISBN: 978-94-6366-444-8. DOI: 10.5074/T.2021.004

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