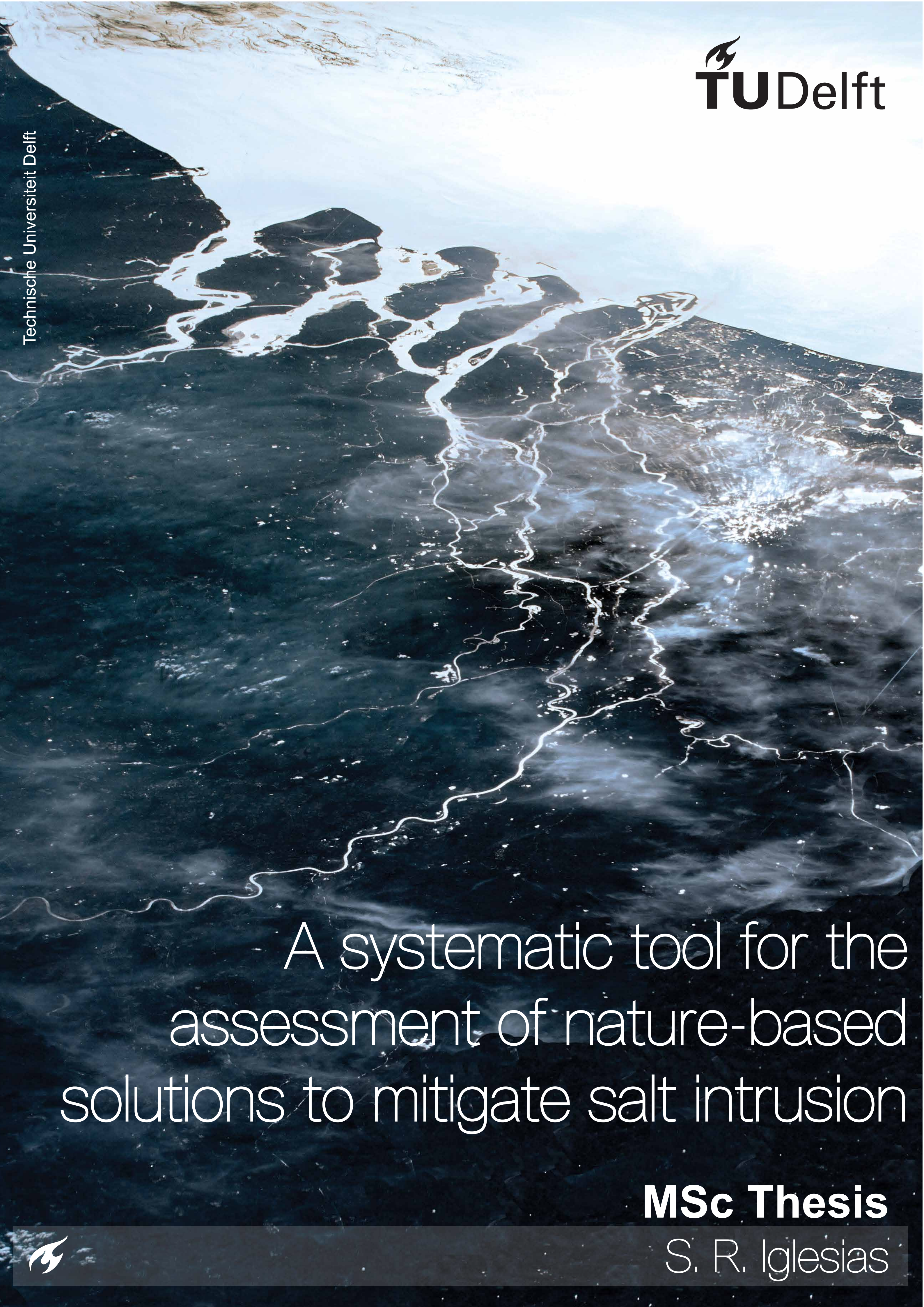

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A systematic tool for the assessment of nature-based solutions to mitigate salt intrusion

MSc Thesis

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A systematic tool for the assessment of nature-based solutions to mitigate salt intrusion

by

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Preface

This research marks the final step to obtain my master‘s degree in Civil Engineering at the Delft University of Technology in Hydraulic Engineering. It is also one step more in the long journey that started two years ago in the other corner of the world, in Argentina. It now brings me to the land of the world’s leading experts in my field where I plan to grow personally and professionally. This thesis research challenged me to push my limits as an engineer and person.

First of all, I would like to express my gratitude to Mark van Koningsveld for encouraging and trusting me to do my thesis within the SALTISolutions Programme and work together with the Ports & Waterways staff. Thank you for chairing my committee, bringing clarity, guiding me in the right direction, and teaching me your vision in hydraulic engineering. These are invaluable lessons for my professional future.

Secondly, my gratitude goes to the rest of my Master of Science Thesis Committee. Thank you, Floor Bakker, for all the mornings and afternoons spent setting up the OpenTNSim model for my study, and thank you, Gijs Hendrickx, for the unconditional support along the way. Research is the latest skill I have learned, so I highly appreciate your guidance and the diligent feedback you provided me numerous times. I would also like to thank Stefan Aarninkhof. You were always willing to take the time to discuss the findings of my research in detail. Your collaboration certainly has helped me understand how to look at and analyse nature-based solutions. Also, I take this opportunity to express my gratitude to Han Meyer and Esther Blom, for providing me with an integrated vision to analyse problems in estuaries. Without a doubt, one of the main motivations in my professional career is looking at problems from a multi-disciplinary perspective. Also, thank you, Lamber Hulsen, for your guidance in using the OSR-model.

Thirdly, I want to express my appreciation to PIANC. Especially to PIANC Argentina and the Argentine Association of Port Engineers (AADIP) for my MSc at TU Delft in The Netherlands. Thank you Raúl Escalante and Sebastián García.

Finally, I wish to say a final word to my girlfriend Vanesa. Thank you for your unparalleled love, help, and advice whenever I needed to. Also, my deep and sincere gratitude to my family and friends for their continuous support. Your encouragement made this master experience an enjoyable journey.

S. R. Iglesias
Delft, February 2022

Abstract

Nature-based initiatives have emerged as potential solutions to problems caused by saltwater intrusion in deltas found globally. The successful implementation of these solutions is enabled partly by a multi-stakeholder approach. However, managing several parallel objectives and achieving transparency between interdependent actors usually requires quantitative knowledge to understand possible collisions of interests. On that account, the present work developed a systematic approach (from now on referred to as the 'comparison tool') aiming to take a step forward and quantitatively compare the objectives of multiple stakeholders interplaying in a delta. As a first approach, the comparison tool is intended to support decision-making to deal with potential conflicts between freshwater supply and port logistics interests. In particular, the present juncture in the Rhine-Meuse Delta in the Netherlands offered a suitable cases study to investigate potential trade-offs generated by the nature-based shallowing (or river bed heightening) of the Rotterdam Waterways as a solution to mitigate salt intrusion.

The comparison tool is founded on the objective-based assessment of Building with Nature (BwN) solutions. The effects of a BwN solution are assessed separately for each functional requirement and then are related in a combined assessment. To test the tool in the Rotterdam Waterways case study, two numerical modelling studies were required. First, the effects of shallowing on the hydrodynamics and salt transport in a partially-mixed estuary were modelled with the Operationeel Stromingsmodel Rotterdam (OSR-model), developed by the Port of Rotterdam Authority. Secondly, changes in meso-scale traffic over the port network were modelled with the OpenTNSim developed by TU Delft, which was coupled with the afore-mentioned OSR. The effects of shallowing on freshwater supply were assessed at two study locations in the Nieuwe Maas River, whereas the effects on port traffic flows were evaluated over a simplified network for seagoing vessels calling at a liquid bulk terminal in the Port of Rotterdam. Finally, performance indicators in line with the operational objectives of freshwater supply and port logistics (capacity and efficiency) were obtained and then compared.

This research delivered a systematic procedure with potential applications to nature-based solutions to mitigate salt intrusion in urbanized deltas. Furthermore, the tool was successfully implemented in the case study, demonstrating how a combined assessment can be performed in these type of problems. The most important outcome entails quantitative trade-offs between port efficiency and freshwater supply over a range of bed level increase from 0.0 m to 3.9 m. In general, results showed that the improvement towards the objective of port logistics always goes to the detriment of the freshwater supply objective while increasing bed level. Also, this study found that a collision of interests between the two types of end-users might worsen for a bed level increase over 2 m. From this turning point, a slight bed level increase leads to a pronounced negative effect on port efficiency, whilst the improvement in freshwater supply is limited. Additional results showed that shallowing could be associated with a benefit on freshwater supply through a decrease in the duration of water shortages. The latter holds for specific environmental conditions of low river discharge and mild wind conditions. Also, this study concluded that shallowing could negatively affect port efficiency due to heavier vessel traffic and more burdensome tidal window restrictions. Findings indicate that the average waiting times of vessels could grow exponentially for a bed level increase over 2 m.

Since the freshwater and port sub-systems were simplified to a certain extent, uncertainty in the results was unavoidably accepted. Notwithstanding these simplifications, this work was meant as a proof-of-concept study. Thus, the aim was not in the completeness and details but rather in demonstrating the main principles in implementing the comparison tool. In this regard, this research lays the groundwork for more comprehensive schematizations of the estuary. In addition, several recommendations for policy-making are proposed, setting a basis for later discussions between freshwater supply and port-related stakeholders in the Rhine-Meuse Delta.

Contents

1 Introduction

Estuaries are dynamic landscapes where fresh runoff water mixes with saline seawater. These coastal embayments provide habitat for fish, birds, and other species. In addition, the fertile land in deltas has supported human settlements throughout history, and the river streams have provided opportunities for transport and trade [Eekelen et al., 2020]. As a result, delta areas have developed into densely populated areas where economic, ecological, and societal interests interact.

In recent decades, freshwater supply in many deltas worldwide has been threatened by the increasing problem of salt intrusion [Rahman et al., 2019, UNESCO, 1981]. In response to societal demands and the need to protect the environment, nature-based philosophies offer infrastructural solutions with a sustainable, multi-functional, and multi-actor perspective [United Nations, 2018] that can be applied to water systems such as estuaries [de Vriend et al., 2015, Laboyrie et al., 2018, Slinger and Vreugdenhil, 2020]. However, any intervention in the estuarine system to solve the salt intrusion problem implies a disruption in the stakeholder arena. Hydraulic engineering solutions affect not only individual interests but also the interaction between them [Laboyrie et al., 2018].

This study is set out to target potential trade-offs amongst stakeholders' objectives within an estuarine system. It intends to capture and quantify these relations through a new systematic method in line with Building with Nature principles [Eekelen et al., 2020, Waterman, 2010]. In particular, it is meant as a first approach in quantitatively comparing the objectives of freshwater supply and port logistics affected by a nature-based solution. This study avails numerical modelling techniques to assess hydrodynamics and salt transport variations in a partially-mixed estuary, and traffic changes in a port network.

1.1. Research context

In many deltas around the world, the issue of salt intrusion has received considerable attention during the last decades. Fresh water used to be taken for granted, but now, in light of future trends of increasing population and climate change, it is seen as a valuable and scarce resource that needs to be preserved [Rahman et al., 2019, UNESCO, 1981]. In preparing deltas for these new challenges, decision-making needs to count on a portfolio of potential mitigation measures for salt intrusion.

Traditional engineering approaches tend to make efforts to meet the primary objective of the project and minimise or compensate for the adverse effects [Linde et al., 2013]. In line with the demands of society, nature-based philosophies have emerged to address the environment and stakeholder interests from the start of the project [Vries et al., 2021a]. However, accepting these types of approach comes with new challenges for successfully implementing nature-based alternatives.

One of these challenges is the capability to use the components of the natural system to deliver a solution that meets multiple objectives related to the many interests at stake [Eekelen et al., 2020]. Different authors in literature realised that an efficient resolution of conflicts between stakeholders depends on a transparent interaction between specialist knowledge and the end-users of this knowledge [Laboyrie et al., 2018, van Koningsveld, 2003]. To achieve transparency, they developed systematic procedures to objectify and rationalise any stage of the design and implementation of Building with Nature solutions [de Vriend et al., 2015, Laboyrie et al., 2018, Vries et al., 2021a]. These procedures are based on the approach called the 'Frame of Reference (FoR)' by van Koningsveld [2003]. The approach enables the formulation of clear objectives systematically, while indicators are defined to quantify and evaluate the success in achieving those objectives. As a result, specialist research produces transparent outcomes to apply in practice.

Furthermore, the FoR approach applies to situations where several parallel objectives are handled, when complying with one objective could go to the detriment of another objective. Here, the management framework would typically intend to keep a balanced overview of the indicators quantifying these objectives. Then, the system can be adjusted in such a way that a desired state is achieved, so management actions should not only address individual aspects but also consider the overall picture [Laboyrie et al., 2018].

However, it is noted that there is not a straightforward method to obtain quantifiable knowledge to trade off the objectives formulated according to the FoR approach. In the literature review conducted for this work, it was found that methods to find quantifiable relations between multiple interests in a nature-based project remain somewhat underdeveloped.

This issue is particularly relevant for implementing measures to mitigate salt intrusion in highly engineered estuaries. Historically, waterborne projects in estuaries have tended to be mono-functional, without due consideration of salt intrusion as a side-effect [Andrews et al., 2017, Luo et al., 2007, Paalvast, 2014, Ralston and Geyer, 2019, Ralston et al., 2019]. Nowadays, there is a strong need for sustainable and cost-effective measures in coastal wetlands that restore and even enhance dynamics in the ambient system [Day et al., 2000]. In estuaries, it includes restoring abiotic conditions of salinity, water level, hydrodynamics, morphology, and water quality, to provide functions from which natural habitats can benefit [Eekelen et al., 2020]. By doing so, infrastructure solutions could create an opportunity to guarantee the provisioning of freshwater resources, keep the competitiveness of port-related activities, and restore a natural state and a more friendly space for humans. Nevertheless, conflict of interests among multiple actors remains a challenge for waterborne projects [García-Onetti et al., 2018, Slinger and Vreugdenhil, 2020]. In this respect, acquiring quantifiable knowledge to trade off these interests can significantly support policy and decision-making.

1.1.1. Context in the Rhine-Meuse Delta

From academic spheres and environmental organisations in the Netherlands, a plea for an investigation was proposed to explore the effect of 'nature-based shallowing' of the Rotterdam Waterways [Meyer, 2020]. This measure is understood as the increase of the river bed level through natural sedimentation processes providing that maintenance dredging operations would no longer maintain the current navigable water depth in the waterway.

First, it is hypothesised that shallowing could have a positive effect on salt intrusion, resulting in benefits for freshwater supply [Meyer, 2020]. Several studies show that the deepening of waterways has increased salt intrusion in estuaries around the world [Luo et al., 2007, Paalvast, 2014, Ralston and Geyer, 2019], which could be used to support the idea that shallowing could have a reverse effect. However, the extent of shallowing's effects on the operation of freshwater supply systems is unknown.

Secondly, the increase of bed level in one of the most busy waterways in the Port of Rotterdam could impose burdensome conditions for the accessibility of vessels. However, it is not clear how efficiency and capacity aspects in the port would be affected, and what is the degree of this effect. Furthermore, it is uncertain how the vessel fleet would adapt to a shallowed waterway.

Moreover, it has been found that neither of these hypotheses has been tested from a multi-actor approach. Here, a better understanding of the implications of such a measure for freshwater supply and port logistics objectives is crucial for policy-making.

1.2. Problem statement

Managing several parallel stakeholder interests within a nature-based project requires the formulation of multiple operational objectives and measurable quantities for each of them. In a step forward using stakeholder objectives formulated according to the Frame of Reference (FoR) approach, the general focus of this study is on understanding how these objectives can be compared quantitatively. This way, the FoR approach could be expanded to find trade-off amongst these objectives.

In urbanized deltas dealing with salt intrusion, the implementation of nature-based solutions can raise many collisions of interests. In addition, the success of such solution depends on the compromises to be made in trading-off these interests. In this respect, it is found that methods to obtain quantifiable knowledge about the interactions between multiple stakeholders remain somewhat underdeveloped, particularly when it comes to understand potential conflicts between freshwater supply and port logistics objectives.

At the present juncture in the Rhine-Meuse Delta, policy and decision-making lacks clear and quantifiable knowledge of what the shallowing solution implies for freshwater supply and port logistics objectives, and the potential conflicts that could emerge from their interaction. In this regard, the focus of this work will be on the effects of shallowing on:

- Salt transport and its relation to changes in freshwater supply performance.
- Traffic flows in the Port of Rotterdam, specifically concerning port logistics performance in terms of port efficiency and capacity.
- The relation between changes in freshwater supply and port logistics objectives through a combined assessment.

1.3. Objective and research questions

The project's research objective is to provide a systematic tool to quantitatively obtain trade-offs amongst multiple stakeholders affected by nature-based solutions. The 'comparison tool' proposed in this research should be able to capture and compare the objectives of end-users formulated according to the Frame of Reference (FoR) approach by van Koningsveld [2003]. Furthermore, it should support decision-making to deal with stakeholder interactions affected nature-based solutions to mitigate salt intrusion. In particular, it is expected to confront freshwater supply against port logistics objectives within the context of an urbanized delta affected by salt intrusion. The latter should take place in a case study involving the nature-based shallowing of the Rotterdam Waterways.

The central question of this research project is:

How can quantitative trade-offs be systematically obtained amongst multiple stakeholder objectives affected by nature-based solutions, and how do these trade-offs apply to solutions that mitigate salt intrusion?

The main research question should be answered through the sub-questions to follow:

SQ1. What existing method can be used to systematically obtain quantitative trade-offs amongst multiple stakeholder objectives affected by nature-based solutions?

SQ2: What are the founding principles, including the ones in the Frame of Reference (FoR) approach, to develop a tool to quantitatively compare the objectives of multiple stakeholders affected by nature-based solutions?

SQ3: What are the required steps to quantitatively compare implications amongst objectives of multiple stakeholders affected by nature-based solutions?

SQ4: What are the tasks to be executed in finding quantitative trade-offs between the freshwater supply and port logistics objectives affected by nature-based shallowing as a solution to mitigate salt intrusion?

SQ5: What are the effects of shallowing the Rotterdam Waterways on freshwater supply and port logistics objectives, and what is the relation between the impact on these two?

1.4. Relevance

This study explores a relationship between conflicting interests playing an essential role in delta management. As a scientific challenge, this research aims to contribute to an integrated societal response to the salt intrusion issue by taking actions to deliver a management tool to evaluate the effects of infrastructure changes on salt intrusion. The goals of this research are, above all, aligned with the planned actions outlined by the SALTISolutions Programme towards the development of a prototype decision support system for saltwater management decision-making for medium to long term measures. It is hoped that this research will contribute to a deeper understanding of the pros and cons of nature-based alternatives, increasing the chances of turning them into mainstream solutions.

1.5. Methodological approach

The methodological approach is divided into two parts. First, a literature analysis is conducted to find a method that can systematically obtain quantitative trade-offs amongst multiple stakeholders. Also, to identify relevant principles in the Frame of Reference (FoR) approach by van Koningsveld [2003] and its adaptations for the objective-based assessment of nature-based solutions. Besides, additional principles outside the FoR approach are required to understand how quantitative trade-offs can be built. Finally, the resulting principles from this process are used to develop a ‘comparison tool’ for the systematic assessment of nature-based solutions.

The second part of the research is a proof-of-concept of the comparison tool aiming to confront the objectives of freshwater supply and port logistics by the underlying phenomena of salt intrusion. To this end, a case study involving the shallowing of the Rotterdam Waterways is set up. The implementation of the comparison tool in the case study requires selecting and performing numerical modelling studies to acquire data about the environmental effects of shallowing. The two main environmental aspects to assess are: (a) Changes in the hydrodynamics and salt transport in a partially-mixed estuary, and (b) Changes in meso-scale port traffic flows. Also, an additional literature review is required to understand the ultimate effect of shallowing on freshwater supply and port performance (capacity and efficiency).

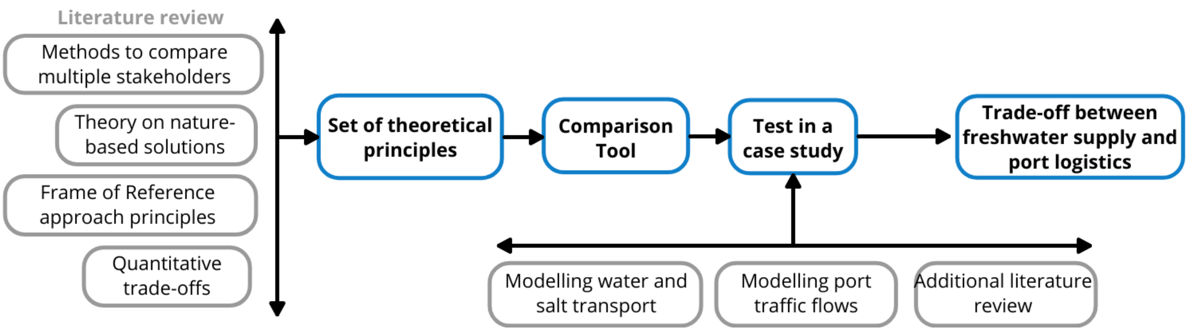

Figure 1.1: Research framework.

Reader’s guide

The structure of the report is divided into six chapters. **Chapter 1** includes the problem definition, research objective, research questions, and the methodological framework of the research. **Chapter 2** includes the literature review. **Chapter 3** presents the process carried out to develop the ‘comparison tool’. First, the general procedure is shown, followed by the tool‘s implementation in the case study involving the shallowing of the Rotterdam Waterways. **Chapter 4** presents an overview of the results obtained from developing and implementing the comparison tool in the case study. **Chapter 5** discusses the results obtained in Chapter 4. **Chapter 6** presents the conclusions by answering the research questions posed in Chapter 1. Then, it provides recommendations for future research and policy-making.

2

Literature study

There are three main goals in this chapter: (a) identify methods to compare implications on multiple stakeholder functions affected by infrastructure solutions; (b) provide with a set of principles needed to carry out the comparison tool systematically; and (c) understand how shallowing affects freshwater supply and port logistics via de underlying problem of salt intrusion.

The literature review is divided into four sections. First, Section 2.1 explores available methods to compare the impact on stakeholder functions. Secondly, Section 2.2 presents the Building with Nature approach. Thirdly, Section 2.3 describes how the Frame of Reference (FoR) approach is used for the objective-based assessment of nature-based solutions. Fourth, Section 2.4 provide important definitions about quantitative trade-offs. Fifth, Section 2.5 presents Building with Nature solutions to mitigate salt intrusion. Finally, in sixth and seventh place, Sections 2.6 and 2.7 provides background knowledge to understand the impact of shallowing on freshwater supply functions and port functions, respectively.

2.1. Methods to compare multiple stakeholders

Infrastructure interventions modify the system and the ambient conditions where multiple stakeholders are supported. The implications for these stakeholders are typically addressed in feasibility studies at the early stages of the planning process. During feasibility studies, the project's initiator would develop conceptual design alternatives and make a first-order assessment of them to identify the most feasible one. Through social and environmental studies and through stakeholder engagement, opportunities and risks that may affect the feasibility of the project are identified [van Koningsveld et al., 2021]. By focussing on the assessment and management of multiple interests, this literature review aimed to find methods that can somehow relate and highlight trade-offs between colliding interests. Three types of assessment methods were found: (1) Non-monetary based and qualitative methods [Ligteringen, 2017, PIANC, 2014b], (2) Monetary-based and quantitative methods [Ligteringen, 2017, PIANC, 2014b], and (3) Methods for *Multi-Objective Decision Making Problems* [Branke et al., 2008, Dodgson et al., 2009, Steuer, 1986]. Relevant aspects of these three are mentioned below.

Type 1: Non-monetary based and qualitative methods can deal with cases in which impacts cannot be quantified. Commonly, Multi-Criteria Analysis or *MCA* [Dodgson et al., 2009] type of methods can be useful [Ligteringen, 2017]. To support the initial assessment of environmental effects of waterborne projects, the *Multi-criteria decision analysis* or MCDA method, as a form of MCA, is a suitable option [Keeney and Howard, 2002]. In the same line, the *Modified URE Method* developed by Federal Institute of Hydrology [2004] is suitable for the same purpose [PIANC, 2014b]. These methods are based on qualitative or semi-quantitative scores, which can be used to compare alternatives or evaluate trade-offs among objectives. In the case of MCA-related methods, a key feature is its emphasis on the judgement of the decision-making team in establishing weights and scores for each criterion, and the subjectivity that pervades can be a matter of concern [Dodgson et al., 2009]. The *Modified URE Method* assess the degree of impact by using effect categories. However, the semi-qualitative nature of this method has certain limitations when assessing the beneficial aspects of methods or in cases where no firm conclusions can be achieved about the effect of a certain measure. Since the qualification of impact is fixed to a set of categories, in these cases the assessment of impact cannot be done with sufficient accuracy. Then, quantitative methods may be needed.

Type 2: monetary-based and quantitative methods include Cost-Benefit Analysis or *CBA* [Regan and Eckstein, 1959], Societal Cost-Benefit Analysis or *SCBA*, and cost-effectiveness analysis or *CEA* [European Commission, 2008]. The first and second ones are mentioned as possible methods to evaluate alternatives and compare aspects in port planning [Ligteringen, 2017]. The second and third ones are suitable for the same purpose, but during the initial assessment of environmental effects of navigation and infrastructure projects [PIANC, 2014b]. These methods provide quantitative information and, thus, quantitative relations can be found by trading off the impact of a measure for multiple aspects. However, there are cases when it is difficult, or impossible, to quantify the impact of an intervention in terms of money [Dodgson et al., 2009, Ligteringen, 2017].

Type 3: This one has a purely-quantitative basis and allows to express objectives in monetary or non-monetary scales. However, the implementation of these methods involves high computational efforts. These are a class of problems where MCA concepts are used, together with interactive computer methods, to directly achieve trade-offs quantitatively and specify the best option [Dodgson et al., 2009]. Problems where the decision variables are infinitely variable, subject to constraints, and where there are multiple objectives, are commonly known as *Multi-Objective Decision Making Problems* [Dodgson et al., 2009, Steuer, 1986]. In the same area of knowledge, these types of methods are also known as *Multiobjective Optimization* [Branke et al., 2008]. The decision variable, or design variable, is a quantity that the decision-maker controls. In practice, changing this variable can affect the performance concerning multiple objectives, and achieving the optimal value for one objective is to the detriment of another. Given the problem's inherent characteristics, there will never be a single solution to the problem. Hence, the main goal of these techniques is to obtain several solutions with different trade-offs among criteria, also known as Pareto optimal or efficient solutions. Optimization is the task of finding solutions that maximize (or minimize) one or more specified objectives while satisfying all constraints. This process involve computer-based procedures to quantify the variables through mathematical or numerical modelling and an optimization algorithm to find the optima of a particular problem [Branke et al., 2008]. The last step of the method consists of the decision-making phase when a single solution is chosen based on the decision-maker's preference. The most important limitation of this method is the high computational effort in generating the set of Pareto optimal solutions. To be able to implement it, recent developments include parallel computations and artificial intelligence in applications to engineering problems with many variables [Branke et al., 2008].

To summarize findings so far, it is seen that literature offers at least three types of methods to evaluate trade-offs among objectives. Then, it becomes clear that finding relations between stakeholders is a concern in assessing impact in infrastructure projects.

A natural progress of this analysis is to understand whether any of these methods can be used to capture and compare the objectives of multiple end-users formulated according to the Frame of Reference (FoR) approach by van Koningsveld [2003]. Here, it should be considered that the FoR approach delivers quantitative indicators. Thus, methods of the type 1 are left out because of its qualitative character. Secondly, this study has made clear a goal to relate dissimilar indicators, which implies that are expressed in different units. Despite that methods of the type 2 can be used to compare quantifiable indicators, they require expressing all quantities in an uniform monetary unit. Hence, these are also put aside. Then, it is seen that only methods of the type 3 can be used to obtain quantifiable knowledge whilst ensuring that dissimilar indicators are traded-off. However, these methods require high computational efforts to acquire data. They also need certain type of computational resources, such as complex algorithms and artificial intelligence, which this research did not count on. Hence, in favour of time-efficiency and considering this research's constrains, type 3 methods select were not selected.

Even though non of the methods found was chosen, basic concepts from Multi-Objective Decision Making Problems (MODM) and Multiobjective Optimisation (MO) methods are valuable to this research, since they can be used to build quantitative trade-offs systematically. More details on how these concepts are used in the context of this research are introduced later on in this report.

As mentioned in the research objective, an overarching requirement for the comparison tool is the capability of assessing under the distinguished multi-objective character of nature-based solutions. The search of literature now continues in this direction.

In the assessment of nature-based solutions, the anticipated environmental effects of a proposed project, including the socio-economic effects, are identified, investigated and evaluated [Laboyrie et al., 2018]. In this procedure, clear receptor-objectives are required so that an overarching integral objective can be built [Laboyrie et al., 2018]. The Frame of Reference (FoR) approach by [van Koningsveld, 2003] can be used, in conjunction Building with Nature principles, to establish these objectives [de Vriend and van Koningsveld, 2012, de Vriend et al., 2015, Eekelen et al., 2020, Vries et al., 2021a]. In other words, the FoR approach can be used to objectively assess the impact of nature-based solutions. This is the reason why this approach gathers the main principles to develop big part of the comparison tool desired by this research.

2.2. Design of Building with Nature solutions

Before going into more detail about the objective-assessment through the FoR approach [Laboyrie et al., 2018, van Koningsveld, 2003], it is crucial to define the Building with Nature (BwN) framework used to design the solutions in the first place. This framework has been applied several times worldwide with significant stakeholder acceptance. Ecoshape and other parties have carried out many successful projects in river and estuaries (Marconi salt-marsh development (NL), Oyster reefs in the Eastern Scheldt (NL), Sustainable river works in Gorai River in Bangladesh). The BwN design philosophy aims to create solutions:

- In harmony with the behaviour of the natural system.
- By letting nature do part of the work.
- In close collaboration with stakeholders and local communities.
- With added value for nature, (local) economy, and society.

To successfully implement a BwN solution, the following ‘five steps approach’ can be applied in any phase of the project development [de Vriend and van Koningsveld, 2012, de Vriend et al., 2015, Eekelen et al., 2020]:

1. Understand the ambient system beyond the primary objective (including ecosystem services, values, and interests).
2. Identify realistic alternatives that use and/or provide ecosystem services, involving experts, decision-makers, and other stakeholders.
3. Evaluate the qualities of each alternative, including natural and societal costs and benefits, and preselect an integral solution.
4. Adjust the selected solution, complying with practical restrictions and governance context.
5. Prepare the solution for implementation in the next project phase, making essential elements explicit to facilitate the uptake.

In the planning and preliminary design phase of the project, the outcome of these five steps is a conceptual BwN design that meets the governance context. At the same time, it complies with all stakeholder requirements and adds value to nature and society according to a multi-objective approach.

2.3. A Method for objective-based assessment of nature-based solutions

The 'Frame of Reference (FoR)' method is used to establish concrete and transparent links between the interests or values that are quantified. Also, the interventions that are proposed and the overall objectives of the project [Laboyrie et al., 2018, van Koningsveld, 2003]. As a result, a systematic, objective-based way of assessing the impact of a measure affecting several interests is set up. The Frame of Reference (FoR) approach includes the following elements (see also Figure 2.1):

- A strategic objective
- An operational objectives
- A decision recipe containing four elements:
    1. A Quantitative State Concept (QSC).
    2. A benchmarking procedure.
    3. An intervention procedure.
    4. An evaluation procedure confronting the operational as well the strategic objectives.

The systematic approach for objective-based assessment and management used in this study is based on [Laboyrie et al., 2018]. In the paragraphs to follow, the principles of this approach are further elaborated.

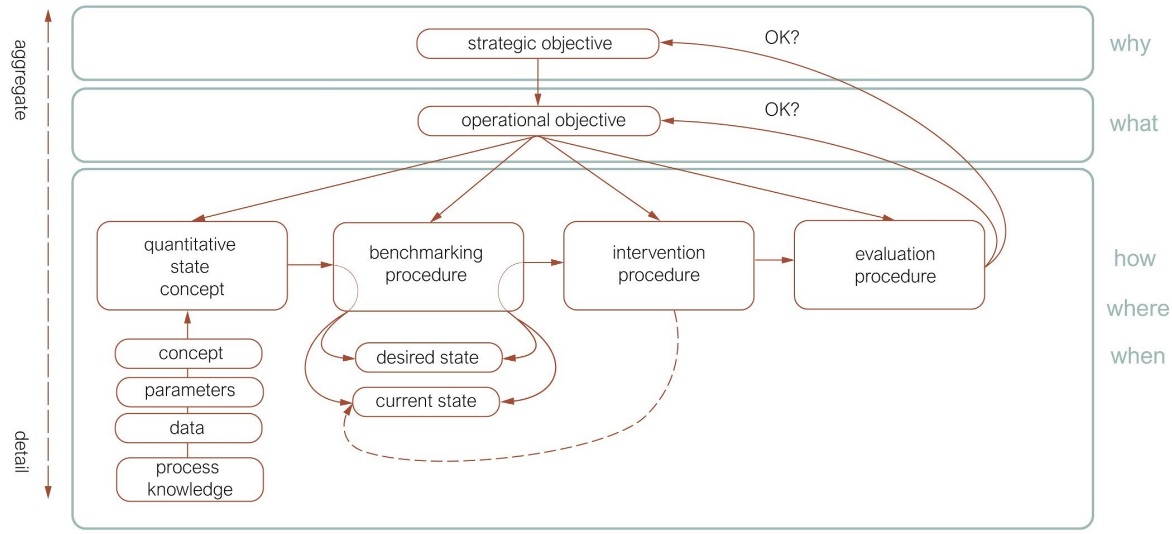

Figure 2.1: Basic 'Frame of Reference' template (scheme by van Koningsveld et al. [2021] licensed under CC BY-NC-SA 4.0). The figure presents the basic framework of the method. It starts by reflecting on the key elements of the decision-maker strategy to define a strategic objective. Then, the conceptual design is broken down into different elements, and operational objectives are defined, stating what needs to be achieved. The operational phase requires further detailing in defining a Quantitative State Concept (QSC), a benchmarking procedure, and an intervention procedure. Finally, the evaluation procedure is carried out by confronting the decision recipe against the operational objective and the strategic objective.

Formulate the strategic objective

The broad objective of the project entails the joint vision embraced by its stakeholders, considering the natural components and the socio-economic context. Hence, the strategic objective should align with this vision. The identification of values and interests, and the specification of the objectives of the project are defined during the conceptual design phase of the project through the 'Five Steps approach' explained in 2.2. After defining the strategic objective, the solution to implement can be broken down into design elements [Vries et al., 2021a]. For each of these elements, an operational objective is formulated.

Formulate the operational objectives
The specification of any operational objective further defines how the natural system interacts with the socio-economic context. Since a certain focus is applied, operational objectives are an imperfect specification of the strategic objective. Therefore, these have to be more concrete than the strategic objectives, specifying performance requirements and limit levels for each of the design elements [Vries et al., 2021a].

The comparison tool to be developed in this research should support managers if they have to deal simultaneously with multiple objectives. In such cases, a strategic objective can be served best with parallel operational objectives. It could happen that measures aimed to benefit one objective adversely affect another. Here, it is important to keep a proper overview of all specified objectives and know how they interact [Laboyrie et al., 2018]. From an integrated management perspective, gaining knowledge about these interactions between objectives can help to minimize the number of conflicts.

Design measurable quantities
The next step is to describe the state of the system or certain aspects of it in an appropriate form that is in line with the operational and strategic objectives. In the FoR method, this is called 'Quantitative State Concept (QSC)'. A better understanding of two aspects is required to develop a measurable approach. First, knowledge of how changes in the system can affect a receptor or interest at stake is required. Secondly, an appropriate tool to quantify the extent of the change and the degree of the impact has to be specified.

Specify how to benchmark the performance of a design
A benchmarking procedure is necessary to make a systematic and objective decision on whether to intervene in the system. An intervention is required when the current or reference system state exceeds a predefined threshold associated with the desired state. The current state and the desired state should be made explicit and preferably expressed in the chosen quantitative state concept. Since this research focuses on the impact assessment of a measure, modelling studies are used to determine the anticipated effects of a measure.

Specify an intervention procedure
An intervention procedure is necessary to help managers in their decision-making. Especially in deciding what measures to undertake to bring the system from the current to the desired state. For this purpose, the type of intervention and the way to carry it out need to be specified.

Evaluate strategy effectiveness
In this stage, it should be assessed whether the operational objectives are met. If this is the case, the next step is to evaluate the management efforts against the strategic objective.

Summary
By drawing on the objective-based assessment method based on the FoR approach, the above six principles are deemed necessary to conduct a successful assessment of Building with Nature solutions. Moreover, several parallel objectives can be simultaneously addressed, from which performance indicators can be obtained for each one of them.

However, the principles stated here do not guide to producing quantitative relations between objectives obtained from the FoR. In particular, the added value of the comparison tool developed in this study intends to build combined assessments by relating dissimilar indicators. Then, it becomes necessary to conduct a literature research to know how quantities can be traded-off.

2.4. Quantitative trade offs
According to Oxford dictionary, the trade-off is 'the act of balancing two things that are opposed to each other' [Oxford Learner's dictionaries, 2021]. A more intuitively definition by Branke et al. [2008] defines

trade-offs as ‘an exchange, that is, a loss in one aspect of the problem, in order to gain additional benefit in another aspect’. Here, concepts from Multi-Criteria Decision Making (MCDM) are used to rename ‘aspects’ as ‘objectives’. In that sense, a more precise definition of trade-off would be:

> ‘A trade-off represents giving up in one of the objectives, which allows the improvement of another objective. More precisely, how much must we give up of a certain objective in order to improve another one to a certain quantity.’ [Branke et al., 2008]

Hence, a trade-off can measure the change in one objective, which goes in the detriment of another. This definition implicitly states there should be two different quantifiable variables. In the context of this research, there should be also an independent variable that influences these two quantities. It should be noted that more than two variables can be traded-off in a similar fashion, although these situations are out of the scope of this research.

Now, concepts from Multi-Objective Decision Making Problems (MODM) and Multiobjective Optimisation (MO), mentioned in Section 2.1, are used to identify crucial elements of trade-offs.

Model to define quantitative trade offs

An essential task in MODM and MO methods is building a suitable model of the problem, consisting of the formulation of certain concepts [Branke et al., 2008, Dodgson et al., 2009]:

- **Decision variables**: These are (physical) quantities that the decision-maker can control.
- **Objective function**: It is a mathematical function, dependent on the decision variables, that translates the solution into a numerical evaluation of that solution.
- **Constraints**: These are equalities or inequalities expressing how the operating environment of the decision-maker limits the decision variable.

In other words, a relation between the decision variable and each objective function should be found to arrive at trade-offs between the objective functions. The latter entails a critical principle to be used in the comparison tool developed in this study.

Moreover, it should be noticed how compatible these concepts are with the FoR approach and the principles found in Section 2.3. In particular, the following three basic steps can be taken jointly with the Frame of Reference (FoR) approach to build a model of the problem and obtain quantitative trade-offs:

1. Schematize the system intervention as quantifiable magnitude(s), which are the decision variable(s) the decision-maker can control. In terms of the FoR, the intervention procedure provides sufficient information to know how the system is manipulated. Constrains in the decision variable(s) imposed by the context should be identified at this point.
2. The relation between the decision variable and the objective function is found in the Quantitative State Concept. For example, a mathematical function of a performance indicator, defined through the FoR approach, could entail the *objective function* defined above. Likewise, these indicators are dependant on the decision or independent variable in the mathematical relation.
3. Once the individual relations are found, the trade-off is obtained by relating two or more objective functions, i.e. two or more performance indicators. For the sake of simplicity, this research uses the term *performance indicators* to refer to these type of variable.

In the last step of the above list, the concepts from MODM and MO methods are used to expand the FoR approach towards a combination of performance indicators. In conclusion, this study has found all the necessary principles to build trade-offs systematically.

2.5. Building with Nature solutions to mitigate salt intrusion in estuaries

This research gathered all the required elements to build a ‘comparison tool’. Now, it is necessary to review relevant concepts about the nature-based solutions on which the tool will be applied.

There is a long history of dealing with salt intrusion through measures in estuaries worldwide. One example is the so-called ‘Trapjeslijn’ or ‘Stair-steps’ executed in the Netherlands during the 1970s, where the bed of the Nieuwe Waterweg was uniformly increased and fixed in the form of steps. This measure proved to be effective in retreating landward excursion of salt, while also allowing shipping operations [Kuijper and van der Kaaij, 2009, van der Kaaij et al., 2010]. In the Mississippi River (USA) another example that proved to be effective is the submerged berm, built as a sandy sill in the bottom of the channel. It acts like a temporal dam holding back the intruding salt wedge and thus mitigating salt intrusion during extreme events [McAnally and Pritchard, 1997]. Despite this local reduction of water depth, vessels still have suitable conditions to enter the estuary. In recent years, close attention was paid to the design of mitigation measures to guarantee freshwater through river works and strategic dredging measures, such as the creation of dredged trenches and bed forms in the Nieuwe Waterweg [van der Heijden, 2018, Wegman, 2021].

In all these examples, the primary objective is to guarantee freshwater supply, but a constant concern is the potential negative impact on shipping operations. That is not that different from the matters addressed in this research. As mentioned in the Introduction (Chapter 1), an essential objective of this thesis is to test the comparison tool for a possible natural-based shallowing solution affecting functional requirements related to: (1) freshwater supply and (2) port logistics. Then, a key step in implementing the comparison tool in the case study is to acquire theoretical knowledge of how changes in the system can affect these two receptors. The following two sections aim to understand better this link.

2.6. Implications of shallowing on freshwater supply in estuaries

The different passages of this section were set out to relate estuary shallowing and the performance of freshwater supply systems via the underlying concept of salt intrusion. By doing this, sufficient knowledge is gained to conduct predictions about the impact of this measure on the freshwater supply function. First, a few crucial definitions about salt transport in estuaries and salt intrusion are necessary.

2.6.1. Salt transport in estuaries

According to [Pritchard, 1967], an estuary is a semi-enclosed body of water that has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage. Another definition states that estuaries are the areas where freshwater and salty seawater meet and interact and where tides in the adjacent shelf sea have a major role in controlling the stratification [Pietrzak, 2020]. In that sense, *stratification* is defined as the process that occurs as a result of a density difference between two flow layers. The density difference is caused by the interaction between fresh water (lighter density water, and source of buoyancy) and salty seawater (denser water).

Estuaries can be classified according to the relative dominance of stratification or vertical mixing (see Figure 2.2). A possible way to distinguish different regimes in estuaries goes as follows: Salt Wedge, Stratified, Partially mixed (or partially stratified), and Well-mixed. Typically, a more stratified structure occurs when the fresh water discharge in an estuary is large compared to the tidal flows, and a well-mixed estuary occurs in the opposite case. Regimes in an estuary can temporarily shift depending on forcing conditions such as neap or spring tides, seasonal variations of river discharge, or episodic storms [Savenije, 2012].

In a salt wedge to stratified flow, there is a horizontal-oriented interface between the two layers of water (Figure 2.2, two sketches on the left), with a clear definition of a freshwater surface layer and a salt wedge underneath. In a well-mixed and partially-mixed structure, the interface is vertical-oriented, resulting in a horizontal gradient of salinity in the direction of the estuary. In the most extreme case, there is no stratification, but a constant salinity value for the entire water depth (Figure 2.2, upper right sketch). To predict the type of estuary, the Estuary-Richardson number can be used [Pietrzak, 2018].

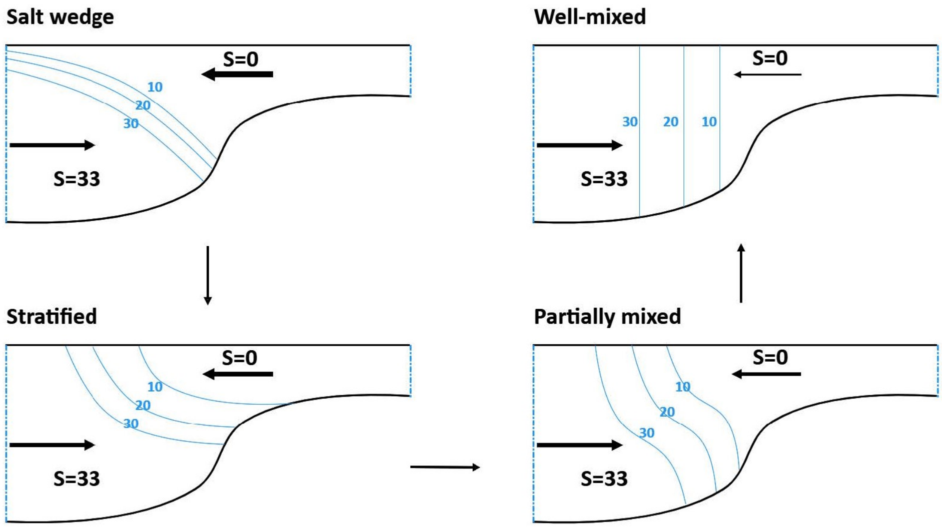

Figure 2.2: Types of estuaries based on degree of saltfresh mixing. Numbers denote salinity in Practical Salinity Units [PSU] [Pietrzak, 2020]

Measurement of salinity

Salinity is an important measurement in estuaries to characterize the mixing of fresh and saltwater. Salinity is commonly expressed in PPT (Parts Per Thousands, 1 PPT = 1000 mg/l), similar to PSU (Practical Salinity Units, 1 PPT = 1 PSU) expressing the total dissolved solids in water. Also, the chloride concentration measures the amount of chloride ions dissolved in the water (mg Cl/l). The relationship between salinity and chloride concentration is as follows [Carritt and Carpenter, 1959, UNESCO, 1981]:

1 PSU = 1.8066 Cl- g/l

Salinity in [PSU] is often used for general considerations about salt intrusion. On the other hand, norms and legal standards for freshwater intake in the Netherlands are generally expressed in terms of chloride content [Huismans and Plieger, 2019]. Therefore, this study uses both PSU and Cl- units.

2.6.2. Relevant processes driving salt intrusion in estuaries

When the upstream movement of salt fluxes cause salinity concentrations to increase above background levels, it is usually referred to as 'salt intrusion' [Herbert et al., 2015]. This phenomenon is driven by three main mechanisms [MacCready and Geyer, 2010]: **(1)** a landward-directed component due to exchange or **estuarine circulation** [Hansen and Rattray, 1967], **(2)** a landward-directed component due to **tidal dispersion** [Fischer, 1979, Okubo, 1973], and **(3)** a seaward component due to **net outflow** by the river [Hansen and Rattray, 1967].

The three mechanisms mentioned above and resulting salt fluxes constantly adapt to changing forcing conditions due to the tide, river discharge, and wind. Also, the geometry of the system influence these mechanisms [MacCready and Geyer, 2010]. The following three parts of this section pay closer attention to the effect of shallowing on these mechanisms. To this purpose, the shallowing measure is understood as a decrease in the river water depth.

Estuarine circulation

The first mechanism, estuarine circulation, is created by a difference in density in mixing seawater and freshwater from the river. Denser water entering the estuary replace the escaping mixture, and as a result, there is a net (i.e. tidally averaged) flow entering landwards near the bottom, which is offset by a net seaward current near the water surface [Geyer and MacCready, 2014]. The resulting pressure drives this circulatory flow pattern over the vertical, which is seaward-directed in the upper part of the flow and landward-directed near the bottom (see also Figure 2.3).

According to the steady-state theory on dynamic salt fluxes balance, estuarine circulation is specially

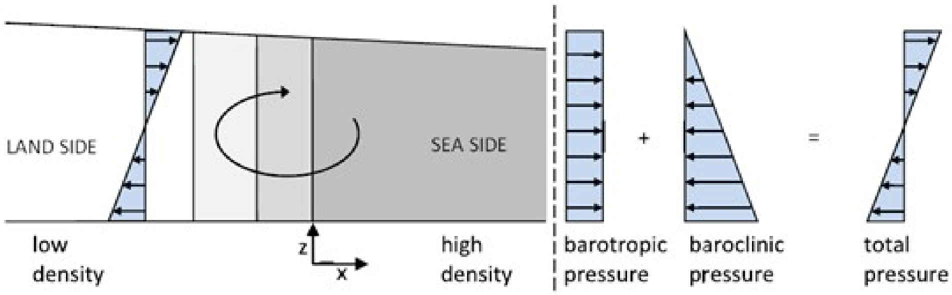

Figure 2.3: Vertical distribution of pressures resulting in the total pressure forcing estuarine circulation [Pietrzak, 2020]. The barotropic pressure is seaward directed, whereas the baroclinic pressure is directed up estuary. The resulting pressure leads to a circulatory flow pattern in which the upper part of the flow is forced seawards while the lower part is driven landwards.

sensitive to the longitudinal salinity gradient [Hansen and Rattray, 1967, MacCready and Geyer, 2010, Officer, 1976]. This gradient increases with the density difference induced by the buoyancy forcing of the river i.e. for larger river run-off. In estuaries exhibiting a larger horizontal salinity gradient, estuarine circulation and stratification is strengthen. In these cases, estuarine circulation may be a dominant factor in driving salt fluxes [Geyer and MacCready, 2014].

Following the same steady-state theory, estuarine circulation is sensitive to water depth. A reduction of the water depth reduces the landward-directed pressure near the bottom. As a result, the density-driven landward-directed velocity in the lower part of the flow decreases with water depth according to a non-linear relation. In other words, the strength of the estuarine circulation and thus the driving mechanism of seawater intrusion decreases with a reduction of the water depth [MacCready and Geyer, 2010].

Additionally, vertical mixing breaks down stratification [Simpson et al., 1990]. As a result, salt intrusion can be reduced. To cause vertical mixing, turbulence energy is needed, which could be supplied by a higher boundary layer turbulence resulting from a water depth reduction [Savenije, 2012]. This hypothesis may not apply to the case of well-mixed estuaries. In this case, vertical stratification is low and there is a high degree of vertical mixing. Hence, the effect of reducing the water depth on vertical mixing is expected to be limited.

Evidence about the effect of water depth is found in practice for the ‘Stair-steps’ project in the Rotterdam Waterways. This measure is an example of reducing water depth in a stratified to partially-mixed estuary [Kuijper and van der Kaaij, 2009, van der Kaaij et al., 2010]. Analogously, increasing water depth can lead to more salt intrusion. Some examples corroborate the latter in studies about channel deepening in a partially-mixed estuary [Ralston and Geyer, 2019], or the Rotterdam Waterways [Hydrologic, 2015].

Tidal dispersion

The second mechanism tidal dispersion. This is referred as the result of estuarine mixing processes during a tidal cycle leading to a net along-channel spreading (diffusion) of salt. Also, lateral circulation leading to transverse dispersion can be relevant in wide estuaries ($h <<< W$) [MacCready and Geyer, 2010].

A lower water depth due to shallowing could result in more effective bed friction, leading to higher flow resistance in the propagation of the tide. However, there are two possible counteracting possible effects on tidal dispersion [Rigter, 1973]:

1. A decrease in the tidal flow upstream at high tide would reduce the strength of the tidal dispersion mechanism through a lower tidal excursion[1]. A lower water depth due to shallowing could result in more effective bed friction, leading to a higher vertical mixing. As a result, salt intrusion can be reduced. This situation could occur in well-mixed estuaries, where stratification is low.

2. In stratified estuaries, the effect of shallowing on salt intrusion is not that straightforward as in the case of well-mixed estuaries. A decrease of the tidal amplitude is associated with lower flow ve-

[1]The tidal excursion is the mixing length of the longitudinal mixing process [Savenije, 2012].

locities and thus a reduction in turbulent mixing such that stratification in the estuary is increased. As a result, the extent of salt intrusion could be enlarged.

Also, in estuaries exhibiting complex patterns, adjacent harbour basins, groyne sections, salt can intrude further landward driven by tidal dispersion mechanisms, such as tidal trapping [Okubo, 1973]. While the main portion of the salt volume is carried on by the current, a smaller part is temporally trapped in these irregularities, harbour basins, or other branches and gradually spreads back into the main flow. Another dispersion-related mechanism enhancing salt transport in the landward direction is tidal pumping [Fischer, 1979]. Tidal pumping can occur due to an asymmetry between ebb and flood in the spatial structure of the flow created by, for instance, bathymetry differences.

Net flow
The third mechanism driving salt intrusion, the net flow, is the effect of river discharge (seaward) and the time-varying tidal prism. The net flow is the only exporting contributor due to seaward flux by river run-off [Hansen and Rattray, 1967].

The velocity of the freshwater run-off is the river discharge divided by the cross-section of the estuary [van der Tuin, 1991]. Therefore, a lower water depth implies a lower cross-section for the same river discharge. By continuity law, this could lead to higher velocities and thus a stronger salt exporting character. Simultaneously, a lower water depth could result in a higher flow resistance in the tide propagation. As a result, the relative contribution of river runoff could increase compared to the tidal prism, which would lead to more seaward salt flux. This hypothesis was tested in the study of a shallowing intervention in the Rhine-Meuse Delta, although the effect in salt intrusion was limited to only a few per cent [Huismans and Plieger, 2019]. To sum up, a decrease of water depth may affect the next flow contributor, although in the technical studies found, results do not lead to a conclusive statement.

Salt intrusion in the Rotterdam Waterways
Under average conditions, the Rotterdam Waterways falls under the partially-mixed to stratified regime [Kranenburg and van der Kaaij, 2019]. Under low river discharge conditions, the estuary remains in the partially-mixed regime but it can become ‘well-mixed’ under certain conditions. The latter is supported by estimations of the Richardson number (see also Appendix A).

The development of salt intrusion results from changes in the balance between the contributors mentioned in the previous section. In the Rotterdam Waterways, the main responsible is estuarine circulation [Kranenburg and van der Kaaij, 2019]. Only in the upper part of the estuary, in the Nieuwe Meuse, tidal dispersion-related fluxes are dominant. Downriver, estuarine circulation becomes less strong under low river discharge conditions and by the increase of mixing agents such as wind, tides, bed friction, and the geometry of the estuary [Kuijper and van der Kaaij, 2009]. However, the contribution of the estuarine circulation becomes negligible during storms. In this case, the main responsible for the largest peaks in salinity is the net flux in the landward direction [Kranenburg and van der Kaaij, 2019].

2.6.3. Performance of freshwater supply in estuaries
Having defined the context in which freshwater supply systems operate, it is now necessary to explain how its performance can be measured. Taking the case of the Netherlands as guidance, this is typically done by looking at *salinization days* as an indicator. So, the effect of a measure can be expressed in the increase or decrease in exceedance duration (in days) of a freshwater legal standard. Likewise, results can be expressed in terms of the frequency of exceedance occurrences [Huismans and Plieger, 2019, Huismans et al., 2018, Hydrologic, 2015, ter Maat et al., 2014, van der Kaaij et al., 2010]. In long term assessment of effects, some studies used the days of exceedance as integers instead of decimals. In this case, the indicator is calculated as the number of daily occurrences which the normative values are exceeded [Hydrologic, 2015].

Two inputs are required to quantify the *salinization days*:

1. A time-series of the chloride content, usually in mg/l units, determined at the water extraction depth of the water inlet. Modelling or measuring salt and water transport in estuaries is required to obtain this information.

2. The legal standard applicable to that reference location according to local, regional, or national legislation. This standard is typically expressed in chloride content units (mg/l) and depends on the different sub-functions (drinking, industrial, agricultural, and nature as the most typical uses). The normative values of salinity depend on site-specific considerations.

Then, the number of salinisation days can be obtained by contrasting the chloride time series against the legal standard.

Summary

As a result of the literature review conducted so far, a hypothesis is formulated to link changes to the bathymetry (i.e. reduction of the water depth due to shallowing) and the performance of freshwater supply via the underlying phenomena of salt intrusion. The final result of the literature analysis is an impact assessment framework gathering the most important cause-effect relations (see Figure 2.4). In implementing the comparison tool for a case study, this scheme is the basis for making impact predictions through modelling studies.

A remark worth mentioning regards the expected effect of shallowing for the case of the Rotterdam Waterways, an estuary highly influenced by estuarine circulation during periods without storm surges. Here, this mechanism plays a dominant role in driving salt intrusion. Since estuarine circulation is weaken by a water depth reduction, it is expected that shallowing has a retreating effect on salt intrusion during periods without wind set-up.

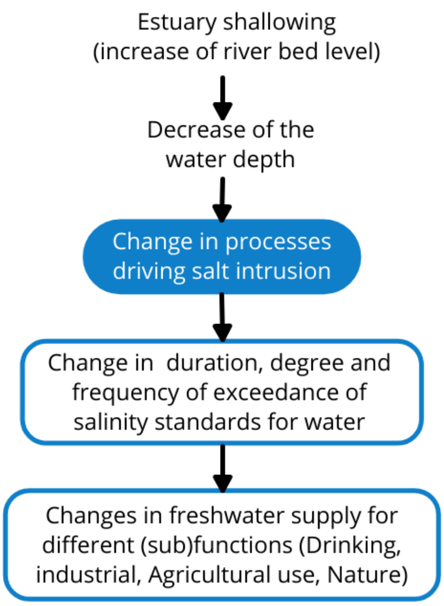

Figure 2.4: Framework for the assessment of implications of shallowing on freshwater supply.

2.7. Implications of shallowing for port logistics performance

This section intends to provide the reader with relevant literature enabling the relation between estuary shallowing and port logistics performance. By understanding how changes in the hydrodynamics of the estuary affect different port processes, changes in port performance can be assessed.

Port logistics performance can be addressed from the aspects of capacity, efficiency, sustainability, and safety [van Koningsveld et al., 2021]. In this research, only efficiency and capacity are considered.

2.7.1. Port systems on the mesoscale level

Traffic flows over the network can be studied at a mesoscale level for most capacity and efficiency-related studies in waterway systems. The study over mesoscopic level is particularly useful in problems that simultaneously require a relatively large study area (from waterway sections to a regional network) and a detailed specification of certain aspects of the network or the agents using it [van Koningsveld et al., 2021]. By looking at the port performance problem at a meso-level, different actors coexisting within a port complex can be comprehensibly included. In terms of the waterborne transport in a port, important actors are [van Koningsveld et al., 2021]:

- Shippers of the cargo.
- Forwarders, responsible for the land transport.
- Shipping lines are the parties operating sea-going and inland shipping vessels.
- Shipping agents, arranging shipping lines and the ports on both ends.
- Port and terminal operators, coordinating the activities within the port.
- Nautical services, parties responsible for vessel assistance such as pilots, tugboats, linesmen, Vessel Traffic Service (VTS)
- Stevedores, responsible for the loading/unloading and storage of goods in a port.
- The port and waterway authorities, responsible for the design, maintenance and management of the infrastructure. Also, they play a key role in managing all port-related interests for the shared benefit.

In this research, the focus is on the agents related to waterborne traffic. That leaves out actors related to the transport of the various cargo flows and those operating on the land side. Hence, shippers, forwarders, and stevedores are not relevant.

2.7.2. Port performance

In a port and waterway system, indicators can be used to identify a chain performance problem. This is done by comparing the estimated value of the indicator against a desired state [van Koningsveld et al., 2021]. However, since performance is a vague concept, it is not easy to obtain indicators straightforwardly. Then, the performance can be 'objectified' by specifying clear design objectives through the Frame of Reference (FoR) approach described in Section 2.3 [Vries et al., 2021b]. Typical port performance indicators relevant for this study are [van Koningsveld et al., 2021]:

- Port capacity or efficiency: cost-effectivenesses (depending on the actor's perspective), such as Net Present Value of a terminal operation, or cost per ton for a certain type of cargo, demurrage costs associated with vessel waiting times.
- Port capacity: throughput or amount of cargo handled per unit of time; maximum amount of cargo that can be handled per unit time at a port terminal.
- Port efficiency: timely delivery, such as percentage of deliveries on time, average delay, waiting times as a factor of service time, among others. In particular, the Average Waiting Time is considered a suitable operational indicator of port efficiency [United Nations Conference on Trade and Development, 1976].

The waiting time of vessels is an important concept for this research, although its definition is not yet provided. The following section fills this gap and elaborates more on the underlying processes.

2.7.3. Port nautical processes

To understand how port efficiency and capacity is affected by interventions to the system, processes representing vessel traffic are defined according to Olba et al. [2018]. These are: (1) arrival, (2) anchoring, (3) navigation, (4)(de)berthing, (5) terminal operations, and (6) departure processes. The nautical processes are linked to certain components of the port nautical infrastructure. Figure 2.5 outlines this relation.

A particular interest for this research resides in the nautical process, which is influenced by tug and pilot assistance, traffic rules, fleet composition, vessel navigation, path choice, sailing speed, and external conditions. These are linked to the following components of the nautical infrastructure: waterway, channel, inner basins, and manoeuvring areas.

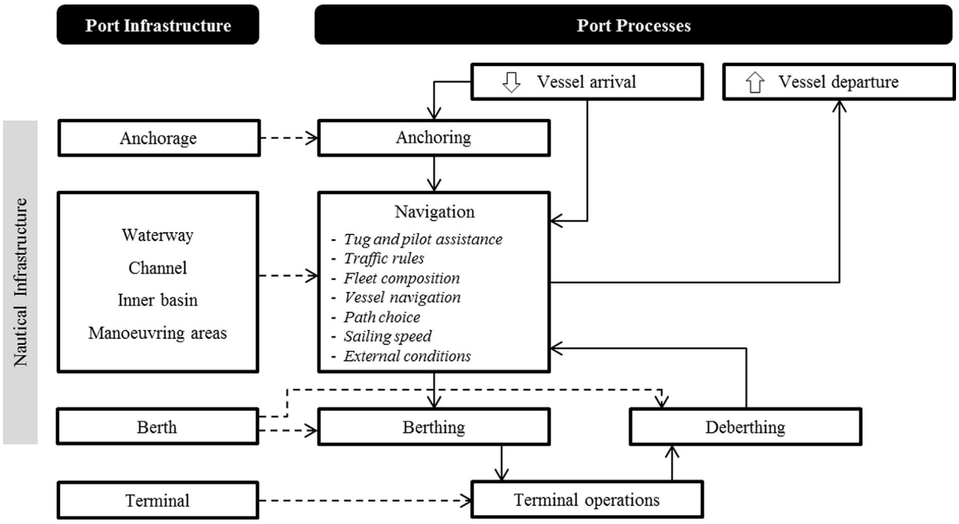

Figure 2.5: Diagram of port nautical infrastructure and processes according to Olba et al. [2018].

The starting point is when a vessel arrives and requests access. The vessel traffic service (VTS) provides information about berth availability, weather, tide, and other external conditions. If it is feasible to enter the port, the traffic situation is checked before permission is given by the Port Authority. Otherwise, vessels wait at the anchorage area. When permission is given, the vessel sails towards the terminal's destination. Next, the vessel sails through the access channel and then to the different parts of the port, such as the waterways, turning basins, and manoeuvring areas. Each of these parts has specific navigation requirements in sailing and manoeuvring, depending on the vessel characteristics. The final step of the arrival procedure is the berthing process when the vessels (un)load cargo. When this operation is completed, vessels are ready to depart. To leave the port, information about weather, tide and other external conditions are checked. Again, if it is feasible to sail out, the traffic situation is verified before permission is given to leave the port or go to a different berthing area.

From the description above, it becomes clear that vessels may not be served immediately. A service without waiting times is economically suboptimal for the Port Authority, whereas too long waiting times make the port less attractive to shipping agents [van Koningsveld et al., 2021]. A terminal operator strives for maximizing berth occupancy. However, according to queueing theory, an increase in berth and anchorage occupancy can lead to an increase in waiting time [Groenveld, 2001, van Koningsveld et al., 2021].

Service time, Sailing times, and Waiting times
By aggregating the main port processes just described to a higher level, it is possible to describe the vessel traffic cycle in terms of the service time, sailing times, and waiting times:

- Service time is related to the time that ships spend at berth for loading/unloading operations [Lee et al., 2003]. In other words, the time spent for terminal operations in Figure 2.5.
- Sailing (or transit) times include the time spent by the vessel sailing from arrival to the anchorage, anchorage to berth and berth to departure.
- Waiting times include the time the vessel spends anchoring and the time between berthing/deberthing minus the service time.

The total time of this cycle is the turnaround time, defined as the time between arrival and departure of the vessel.

2.7.4. Vertical design of channels

As said earlier, nautical process are the most relevant process for this work. Since the aim is to study a river shallowing measure, the bed level of the waterway, channel, inner basins, and manoeuvring areas are affected. Hence, it becomes necessary to provide certain definitions about the vertical design of these elements. Shallowing does not affect horizontal dimensions, such as width, and thus are not considered. In this study, the focus is on the main factors to determine channel water depth. According to PIANC [2014a], these are:

- Water level and tidal current factors.
- Ship-related factors.
- Bottom-related factors.

Based on the concepts from PIANC [2014a], the following subsections deal with important definitions and concepts about these three factors.

Water Level factors

All channel depth factors should be related to the same datum level. For example, in the Netherlands, elevation data is often given concerning Nieuw Amsterdams Pijl (NAP).

In addition, the space and time-varying water level due to tides, surges, and river flow determines the available water depth in the channel at a specific moment in space, at a particular location. In some cases, such as the Port of Rotterdam, deep-draught vessels can only sail in the channel during high-tide windows. This is commonly known as 'vertical tidal window'. Additionally, strong currents may affect the manoeuvrability of vessels. For nautical safety reasons, arrivals and sailings can be restricted to the part of the tidal period with the lowest currents, in what is commonly called 'horizontal tidal window'. The combination of vertical and horizontal tidal restrictions may cause the arrival and sailing nautical processes to be restricted to certain time lapses in the tidal cycle, lading to downtimes during which the port is not accessible.

In the case of appreciable tidal elevations or long tidally influenced channels, a difference must be drawn between the sailing process for inbound and outbound ships. During the inbound transit, vessels sail in the same direction as the tidal wave propagates. For instance, an inbound vessel could start sailing through the channel on a rising tide, reaching the terminal during high tide. However, outbound vessels experience different water levels. During the outbound transit, the vessel moves in the opposite direction to the tide, experiencing a much faster and larger vertical variation. In a similar example, the outbound vessel would start on a rising tide at the terminal, passes high tide halfway during the transit, and reaches the sea at low tide. In other words, the vessel experiences a faster water level variation and has a shorter tidal window to leave the port. In conclusion, more attention must be paid to the design in the case of outbound ships with maximum draught transiting a long tidal channel [PIANC, 2014a].

Ship-related factors

There are two main ship-related factors [PIANC, 2014a]: the static draught (D) and Gross underkeel clearance (UKC) (Figure 2.6). The static draught is the vertical distance between the waterline and the bottom of the hull (keel), and it is defined for the 'design vessel' laying still in seawater. When a vessel sails in freshwater, the buoyancy decreases, and the vessel sinks, increasing the draught. The difference between these two draughts is known as Freshwater Allowance (FWA).

The distance between the keel and the nominal bed level, or Maintained Bed Level (MBL), is the Gross under keel clearance (UKC). The FWA is one of the components of the gross UKC, although there are many others. For more description about the different components of the Gross UKC, the reader is referred to [PIANC, 2014a] .

In some ports, such as in the Port of Rotterdam, the policy indicates distinct values of FWA and UKC (Section A.4.2). FWA is expressed as a percentage of the draught according to different port sub-areas. Landward sub-areas have a larger density difference, and hence a higher FWA. Also, the UKC policy is defined for different waterways and port basins within the port.

Bottom-related factors

An important distinction is made between the natural or actual bed level that results from dredging activities and the guaranteed bed level defined by the port authority or Maintained Bed Level (MBL). The first one is called ‘channel dredge level‘ and defines the real water depth in the channel, whereas the MBL is above the latter and defines the available water depth for shipping (see Figure 2.6). The difference is the safety margin to account for uncertainties in the dredging works and surveying. Also, a safety margin could be chosen to avoid recurrent dredging maintenance works.

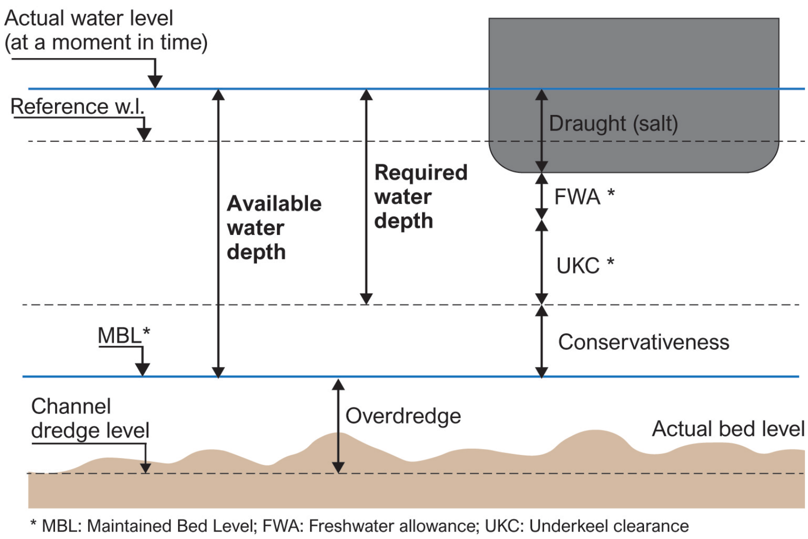

Figure 2.6: Relevant parameters in vertical design of vessels. In particular, the figure sketches the available and required water depth at a moment in time (image modified from de Jong [2020]).

2.7.5. Effect of decreasing water depth on tidal windows

Here, shallowing is understood as a reduction in the water depth of the waterway. This subsection is set out to explain how this system intervention can affect waiting times due to tidal windows.

In some ports, there is a combination of vertical and horizontal tidal windows. Tidal windows have an important effect on port operations and performance as a time-limiting condition [Olba et al., 2015]. At a specific moment in time, for a given location, a vessel can sail in the waterway if the available water depth is larger than the required water depth. Simultaneously, cross-currents should be sufficiently low. In this research, the accessibility of vessels is stipulated by using the approach according to the Port of Rotterdam policy [de Jong, 2020]:

- Vertical tidal window condition at a certain time: $h_{req} < h_{av}$
- Horizontal tidal window conditions at a certain time: $v_{current} < v_{critical}$

The required water depth can be computed as it follows [de Jong, 2020]:

$$h_{req} = T + (T * FWA) + UKC \tag{2.1}$$

With:
UKC: Under Keel Clearance policy defined by the port authority. It can be expressed in m or as % of the vessel‘s draught.
FWA: Freshwater allowance policy defined by the port authority.
T: Design vessel’s draught.
$v_{critical}$: critical-current velocity stipulated by the policy for a certain controlling point.
For a certain moment in time and space, the available water depth is determined as:

$$h_{av} = \eta_{WL} - MBL_{NAP}[m] \tag{2.2}$$

With:
η_{WL}: Water level at a certain moment in time and space (in NAP m)
MBL_{NAP}: Maintained Bed Level (in NAP m)

Then, to calculate the available water level, the MBL needs to be designed. Also, due to tide-varying water levels, a sailing vessel in a stretch of the waterway encounters an available water depth at the beginning and a different value at the end. A possible way to sort this out is to use the approach used by the Port of Rotterdam to determine the MBL [de Jong, 2020]:

$$MBL_{NAP} = -h_{req} + (HW_{99\%} - \Delta H) \tag{2.3}$$

Where:
ΔH: lowering of water level during transit (in m), depending on whether it is an outgoing or ingoing transit, and the sailing distance and vessel's speed.
$HW_{99\%}$: measured high water level (w.r.t. NAP) that is exceeded by 99% of the high water levels [m], based on real data. The port policy defines the % of accessibility. In simpler words, this parameter is the elevation of the vertical tidal window restriction.

The last equation relates the MBL with the vessels' required depth and the water levels in the waterways. Now, it is possible to examine what the impact of shallowing would be, based on this equation. For a fixed vessel draught (i.e. a fixed required water depth), an increase in bed level could lead to a higher *measured high water level* $HW_{99\%}$. In other words, to comply with its policy, the port would need to raise the high water level restriction. That way, a sufficient available water depth can be guaranteed for 99% of the time. However, a higher restriction can have consequences for the available tidal window. When it is not feasible to enter the port, vessels wait at the anchorage area until the water level is sufficiently high. Since the vertical tidal window became more restrictive, the waiting time at the anchorage area is longer. This situation is illustrated in Figures 2.7 and 2.8. The increase of waiting times results in negative effects for the network efficiency and capacity, since anchorage areas are occupied by vessels that cannot sail in. Also, berths are occupied by vessels that cannot sail out, blocking the arrival of incoming vessels.

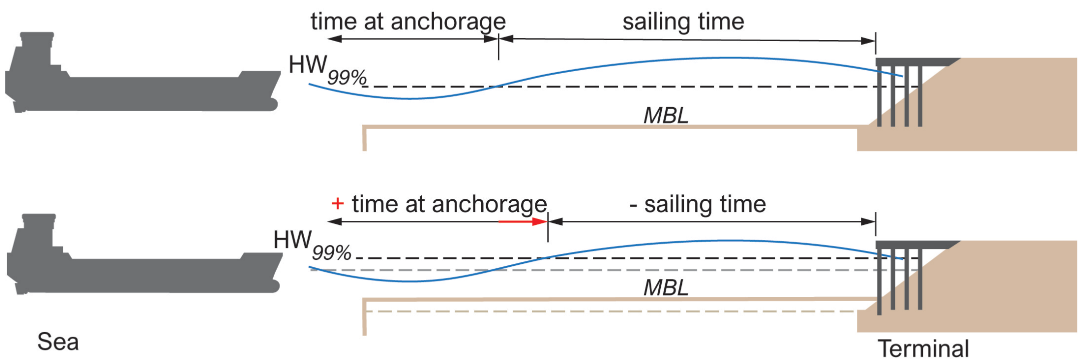

Figure 2.7: Effect of estuary shallowing on waiting times for an inbound vessel. The figure represents a typical seagoing vessel entering the port. The tidal wave is depicted in blue. The upper and lower sketches contain the situations pre- and post-shallowing, respectively. The sketched bed level corresponds to the maintained bed level (MBL). $HW_{99\%}$ is the elevation of the tidal window restriction specified by the port policy, in NAP m. In the upper sketch, vessels wait a certain time at anchorage until the water level matches the $HW_{99\%}$. In the lower sketch, the bed level increased with respect to the previous case. Since the available water depth is now lower, the port needs to specify a higher $HW_{99\%}$ to provide the level of accessibility. However, the time vessels have to wait at anchorage increased (see red arrow).

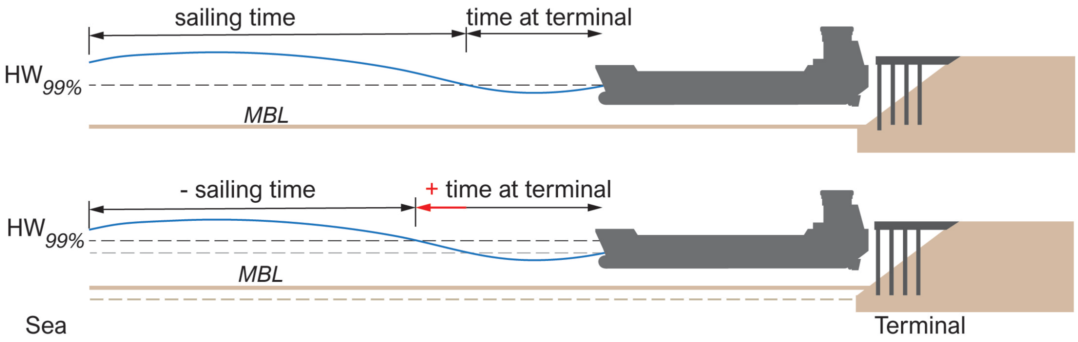

Figure 2.8: Effect of estuary shallowing on waiting times for an outbound vessel. The figure represents a typical seagoing vessel leaving the terminal. The situation is analogous to the one presented in Figure 2.7. In this case, shallowing leads to longer waiting times of vessels at the terminal trying to depart.

Summary

To sum up, a link between shallowing and port efficiency and capacity entails a new hypothesis. An essential concept obtained from the literature is that a decrease in water depth via shallowing is expected to increase vessel waiting times with the subsequent negative impact on network efficiency and capacity. The final result of the literature review conducted is an impact assessment framework gathering the most important cause-effect relations (see Figure 2.9). In implementing the comparison tool for a case study, this scheme is the basis for making impact predictions through modelling studies.

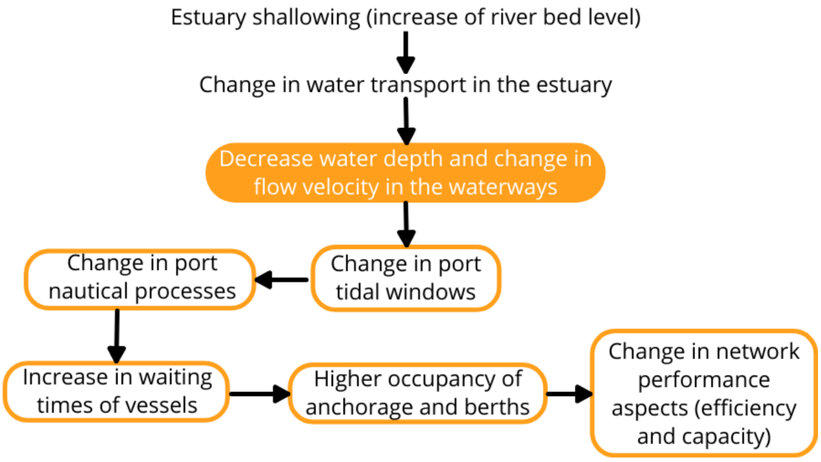

Figure 2.9: Framework for the assessment of implications of shallowing on port efficiency and capacity.

3

Method

This chapter builds on the literature review of Chapter 2 to present how the comparison tool was developed. Then, it presents the methodology to implement the tool in practice. The chapter is divided into three main parts. First, section 3.1 describes the general steps of the comparison tool. Then, Section 3.2 briefly describes the case study that is used to implement the comparison tool. Finally, Section 3.3 describes the steps followed to implement the comparison tool for the shallowing of the Rotterdam Waterways.

3.1. Development of the comparison tool

The tool's main requirement is the capability to align with nature-based solutions through the outcomes of the Frame of Reference (FoR) approach. To this end, six principles identified in the FoR approach should be followed (see also Section 2.3):

1. Formulate the strategic objective by reflecting on the overarching vision for the natural system and the socio-economic context.

2. Formulate the operational objectives by reflecting on the interaction between the natural system and the socio-economic context.

3. Design measurable quantities, or indicators based on the operational aspects of the stakeholder, and the appropriate tools to quantify the indicators (Quantitative State Concept).

4. Specify how to benchmark the performance of a design. The benchmark is done by comparing the current state against the desired state based on the Quantitative State Concept previously defined.

5. Specify an intervention procedure i.e. the way and the degree in which the system is manipulated to bring it to the desired state.

6. Evaluate the effectiveness of the decisions made by reflecting on the operational and strategic objectives.

By following these six principles, individual assessments can be performed for several operational requirements. Also, in Section 2.1, different methods applicable to the assessment of infrastructure measures were analysed. It was explored whether these methods could capture and compare indicators obtained from the FoR approach. This study did not select any of them to continue the research, but instead took basics concepts from Multi-Objective Decision Making Problems (MODM) and Multiobjective Optimisation (MO) methods. Concepts emerging from these methods can be used to effectively trade-off objectives and indicators obtained from the FoR approach.

Then, as an expansion of the multiple assessments conducted within the FoR framework, a seventh principle concerning quantitative trade-offs is defined. According to this principle, quantitative relations between multiple objectives require identifying a dependence between *decision variable(s)* and *performance indicators*. First, the decision variable is the independent variable that the decision-maker can control. Secondly, the performance indicators are quantities dependent on the decision variables, and these are expressed as numerical evaluations of the indicators designed according to the FoR approach. Only then, multiple *performance indicators* can be traded-off by the inherent *decision variable(s)*.

3.1.1. Description of the comparison tool

In brief, three main steps are proposed. To initiate the comparison tool procedure it is asssumed that a conceptual design developed according to the Building with Nature approach is finished ('Five steps approach for BwN solutions' as presented in Section 2.2). Then, the following three steps are followed:

1. The system intervention is schematised from the conceptual Building with Nature design. It is specified how the system is manipulated through changing the *decision variable(s)*. This variable is a measurable quantity on which the decision-maker has control. For instance, nature-based shallowing can be schematized 1-dimensionally as *bed level* or *bed level change*.

2. A objective-based assessment via the Frame of Reference approach is applied repeatedly, each time for a different stakeholder objective. This step entails the principles one to six in the list presented previously. First, an overall strategic objective can be formulated for all stakeholders (1st principle in the list). Then, the remaining stages in the FoR recipe are performed separately for each stakeholder (principle 2nd to 5th in the list) to obtain several *performance indicators*. The most important outcome of this process is the individual assessment of effects for each stakeholder objective. Such an assessment can be expressed as a quantitative relation between the *decision variable(s)* and a *performance indicator*.

3. Dissimilar *performance indicators* are related to enable a combined assessment. In this step, the seventh principle in the list is used. The *performance indicators* in Step 2 are connected by the inherent *decision variable* defined in Step 1. The outcome of the comparison tool is a quantitative trade-off between several stakeholder objectives affected by the same system intervention. This trade-off can be presented through a visualisation showing how improving one stakeholder's performance is to the detriment of another stakeholder while moving along the curve. This last step is where the comparison tool comes into play to introduce a new feature, expanding the objective-based assessment through FoR.

The description of these steps is accompanied by a scheme presented in Figure 3.1.

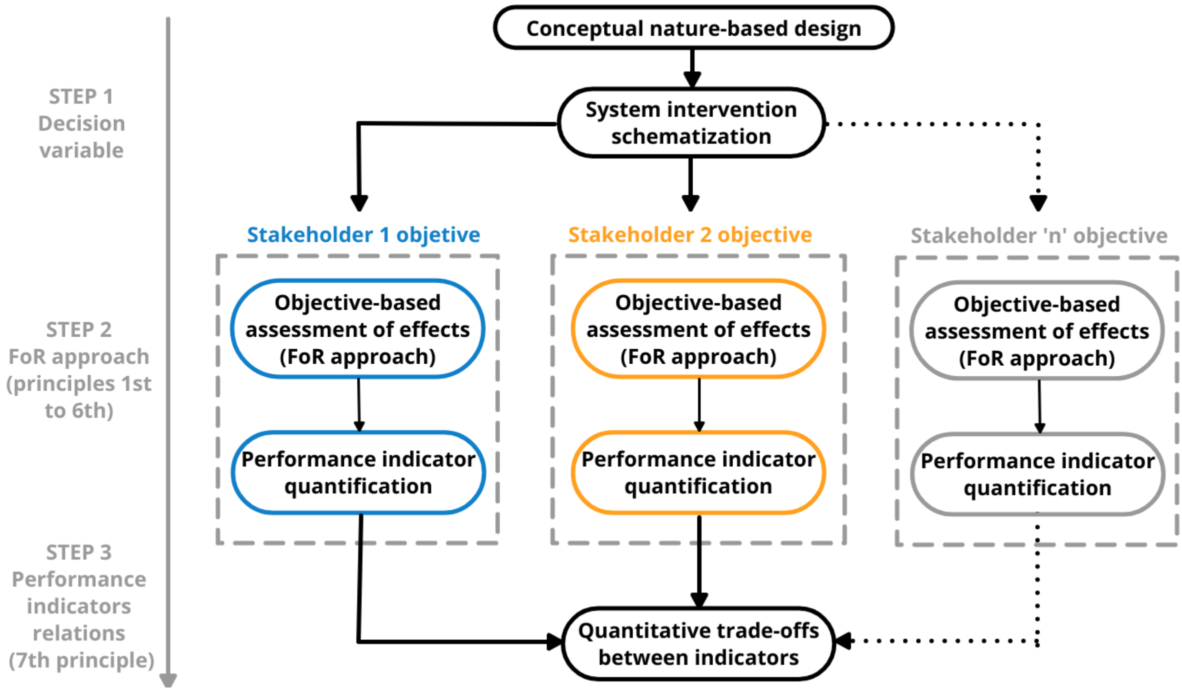

Figure 3.1: Comparison tool to find quantitative relations between the impact of nature-based solutions on multiple stakeholder functions. The figure presents a scheme for implementing the tool. On the left side of the figure, the steps are indicated together with the principles taken from the literature. The comparison tool is initiated by a conceptual Building with Nature design, which is schematised to define a decision variable (Step 1). Then, several parallel and individual assessments are performed through the FoR approach (Step 2). Finally, the Step 3 is where the comparison tool comes into play to introduce a new feature, combining the indicators quantified in the previous steps to build trade-offs.

3.2. Case study

To evaluate the comparison tool's effectiveness, this study chooses the case study of the Rotterdam Waterways. The implementation in the case study aims to be a proof-of-concept of the comparison tool. For this reason, the complex interaction of stakeholders in the estuary was simplified to the relation between freshwater supply and port logistics functions.

The Rotterdam Waterways is the most seaward part of a much larger estuary, the Rhine-Meuse Delta (RMD). This area was chosen for several reasons:

- A conflict of interests between port logistics and freshwater availability is clearly in the heart of the feasibility studies of a project. Experiences in the area show that navigation projects can put port interests at odds with freshwater supply-related stakeholders [Arcadis, 2015].
- In terms of salt intrusion management, it gathers all the characteristics to represent hundreds of deltas worldwide. In that sense, it is defined by the SALTISOlutions Programme as the preferred 'global' lab in which to determine the impacts of natural and anthropogenic changes to the system on salt intrusion [Pietrzak, 2018].
- There is sufficient open-source information to conduct complete and accurate modelling studies (waterinfo.rws.nl). Moreover, Dutch private and public organisations have developed many types of numerical modelling tools during the past 20 years that are available for the prediction of salt intrusion [ter Maat et al., 2014].

3.2.1. Freshwater supply system

The Rhine-Meuse Delta (RMD) is where the Rhine and Meuse rivers meet the North Sea. It is a complex network of many branches with two main sub-areas. On the northern part, the rivers Nieuwe Maas and Oude Maas converge to the Nieuwe Waterweg, the only open connection to the sea and responsible for most of the salt entering the estuary. On the southern part, flow is regulated by the Haringvliet sluices, so the Hollandsche Diep and Haringvliet rivers are freshwater bodies for most of the time. When the Haringvliet sluices are closed, water flow to the nothern part through the rivers Spui and Dordse Kil. On the other hand, river run-off from upstream is transported through the rivers Waal (~ 72%), Maas (~ 12%), and Lek (~ 16%)[1]. Discharge in the system is highly seasonal.

Freshwater in the estuary is used for drinking water, agriculture, flushing, industry, and nature [National Delta Programme 2021, 2020]. Water intakes is placed all over the area, with important points along the Hollandsche IJssel, the Lek, the Spui, and the Nieuwe Maas. For more information about the type of usage function and the areas served by the different water inlets of the freshwater supply system, the reader is referred to the Appendix A. For the studying of this case, saltwater intrusion into the groundwater of coastal aquifers is not addressed, as the interaction of groundwater with the surface water of the inland waterway is not often significant [PIANC, 2021].

For this case study, two reference locations were chosen at Brienenoordbrug and Boerengat (see Figure 3.2). Both are located in the Nieuwe Maas. Boerengat is a water inlet, and Brienenoordbrug is a monitoring point of the National Water Monitoring Network of the Rijkswaterstaat (see also LMW). At this location, salinity is measured at an elevation of NAP -6.50m and NAP -2.50 m. On the other hand, the Boerengat water inlet supplies freshwater for agricultural areas in the Schieland and Krimpenerwaard Water Board. Here, it is assumed salinity is is measured at the water extraction depth of NAP -2.5 m.

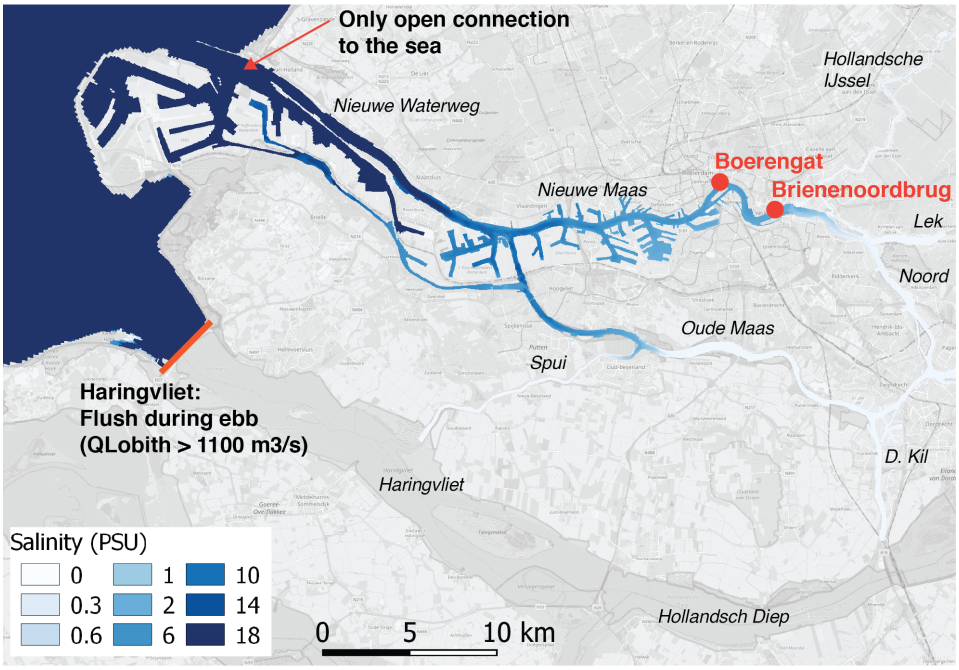

Figure 3.2: Reference locations used in the modelling study to quantify salinity, including an additional water inlet at Bermisse Zoud, located in the Spui. An analysis of the performance of this inlet is discussed in Chapter 5. Also, the figure shows a typical salinisation event occurring during low river discharge (Q at Lobith 1000 m3/s) without storms. The darker the blue colour, the larger the salinity. The figure shows High Water Slack salinity at approximately the water suction depth of inlets. The highest values salinity values (18 PSU) are observed from the estuary mouth up to Maasluis. Also, non normative salinity values (above 0.3 PSU) intrude further of Boerengat and Brienenoord, situation leading to water shortages.

Different types of sanitisation can occur in the RMD depending on the environmental conditions [ter Maat, 2015]. According to de Vries [2014] there are four types of salinisation events (see also Appendix A). In this case study, the focus is on a salinisation event called 'Type 0' that occurs during extremely low river discharge (< 1100 m3/sec measured at Lobith) and normal tidal conditions (i.e. without wind set-up). This event is expected to have a significant effect on the performance of the Boerengat inlet.

[1]Values derived from 2000-2019 time series of average monthly discharges for each river, obtained from the Asset Management Department of the Port of Rotterdam Authority.

In the Rhine-Meuse Delta region, the operation and objectives of the freshwater system are regulated by the *Decree on Quality Requirements and Monitoring for Water 2009* (BKMW 2009), based on the standards for the quality of the surface water set by the European Water Framework Directive (WFD). A widely used supporting parameter of this legislation is the chloride content. In the case of the water inlet at Boerengat, the maximum hourly value of the chloride content cannot exceed 400 Cl- mg/L within one day [Hydrologic, 2015]. For nearby water inlets used for drinking or industrial purposes, the threshold is typically set at 150 Cl- mg/L. If this threshold is exceeded, the water company must take measures to comply with the legal requirements. The nature of possible measures depends on local circumstances. If no other options are available, a possible consequence is water shortage [Werkversie Helpdesk Water, 2018].

3.2.2. Port system

Intensive port operations characterise the Rhine-Meuse Delta. The Port of Rotterdam is the largest seaport in Europe and the world's largest seaport outside of East Asia. Every year, around 28,000 seagoing ships and 92,000 inland vessels call at Port of Rotterdam [Port of Rotterdam Authority, 2020]. An overview of the different port areas is depicted in Figure 3.3. This study focuses on the areas accessible through the Nieuwe Waterweg and Nieuwe Maas waterways. It includes the harbour basins and terminals in the Botlek and the 1st, 2nd, and 3rd Petroleum Haven areas serving a large petrochemical hub with great relevance for many supraregional economic activities. The Koole terminal, located at the 3rd Petroleum Haven, was chosen as the network destination in the traffic model. Further argumentations about this choice are found in the next section.

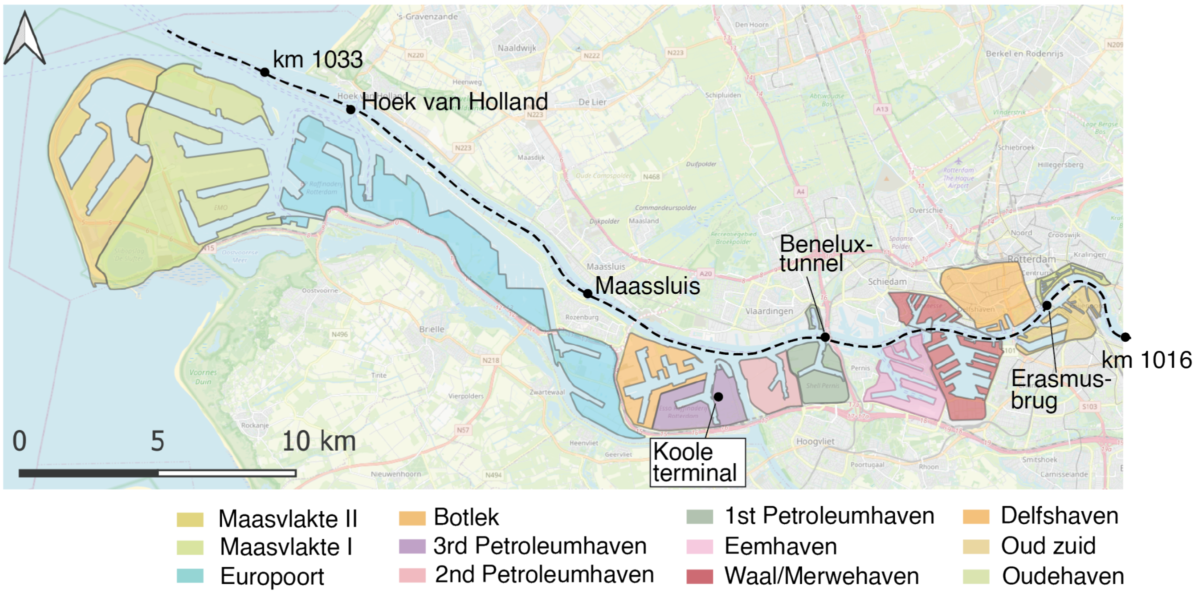

Figure 3.3: Map of the Port of Rotterdam areas, from Maasvlakte 2 to the city port (Oudehaven). Also, the figure presents seven landmarks along the waterways. The exact location of these points can be found in Figure 3.4. In particular, the map highlights the Koole terminal in the 3e Petroleumhaven.

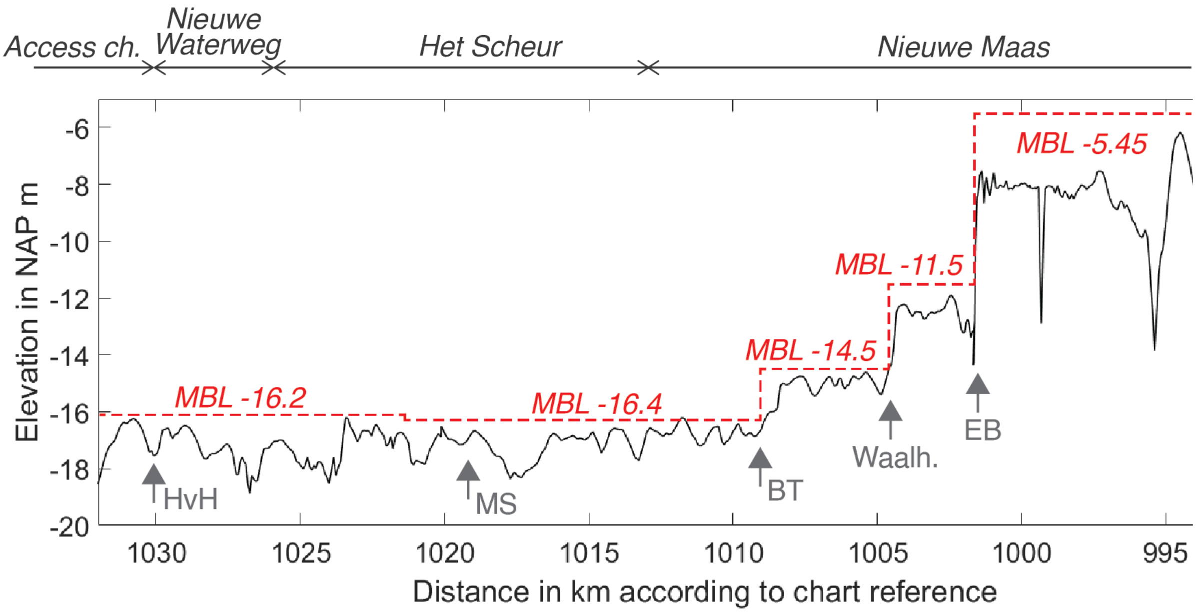

Figure 3.4: River bottom bathymetry in the Rotterdam Waterways. The figure shows, in dashed red line, the Maintained Bed Level (MBL) along the Nieuwe Waterweg and Nieuwe Maas, according to the harbour chart of the PoR [Port of Rotterdam Authority, 2021]. Also, the actual bed level is depicted in black solid line.

The navigable river stretch understudy starts at the Erasmusbrug over the Nieuwe Maas, and ends at the North Sea. In the most offshore part, the shipping access channel Euro-Maasgeul connects to the seaward seaport and the Nieuwe Waterweg. It provides access to the landward seaports between the Botlek and the city of Rotterdam via connections to *Het Scheur*[2] and the Nieuwe Maas rivers. The Maintained Bed Level (MBL) in this part increases according to a stair-steps configuration, building up in four steps from NAP -16.4 m in the seaward edge up to NAP -5.45 m near the city center (see also Figure 3.4).

3.2.3. Choice of the case study terminal

It was chosen to focus the study on a particular terminal to obtain measurable port efficiency and capacity results. This choice is based on the following requirements:

- The terminal and related shipping operations should be directly affected by the shallowing of the Nieuwe Waterweg.
- It should be part of the Port of Rotterdam's oil and chemical industrial cluster and, thus, handle liquid bulk cargo. These port areas have the potential to be developed into biofuels, biochemical and/or hydrogen clusters in future scenarios of fast energy transition [van Dorsser et al., 2018]. Therefore, it would be interesting to consider a liquid bulk terminal that can be used to compare different future scenarios of low and fast energy transition.
- It should be capable of handling the largest-draughted vessels in the Nieuwe Waterweg because they determine the MBL's values of the channel and port basins.

The Koole terminal handles liquid bulk in chemicals, mineral oil products, acids, biofuels, and base oils. Cargo is (un)loaded at berthing points placed on jetties or the quay wall. There is a total of seven berths in which seagoing vessels can breast, from which five of them can serve vessels > 5000 DWT. Also, six berths are dedicated to inland vessels. That makes a total of 13 berthing points. Additional details about the Koole terminal are presented in Appendix A.

[2] In the following pages of this report, the combined river section consisting of the Het Scheur and the Nieuwe Waterweg is simply referred to as the *Nieuwe Waterweg*.

3.3. Implementation of the comparison tool in a case study

In this section, the comparison tool is tested for the case study of the Rotterdam Waterways. The goal is to obtain a combined assessment of the impact on freshwater supply and port logistic functions affected by shallowing of the waterways.

3.3.1. Conceptual design of nature-based shallowing

The concept of shallowing is understood as the increase of the river bed level through natural sedimentation processes. Due to the higher position of the bed, a milder land-water transition on the banks is created, which can increases the chances for the restoration of typical delta natural habitats and a new type of urban landscape [Meyer, 2020]. As a result, the Nieuwe Waterweg river is reshaped to a shallower and narrower cross-section (see Figure 3.5). It is noted that this research focus only on the 1-dimensional increase of the bed level, but not on the horizontal changes in the cross section.

To continue the comparison tool procedure, it is assumed that nature-based shallowing has been identified as a realistic conceptual alternative in the design process according to the Building with Nature approach (see Section 2.2). Furthermore, it is assumed this is the chosen option over other nature-based alternatives attempting to mitigate salt intrusion (e.g. submerged sills).

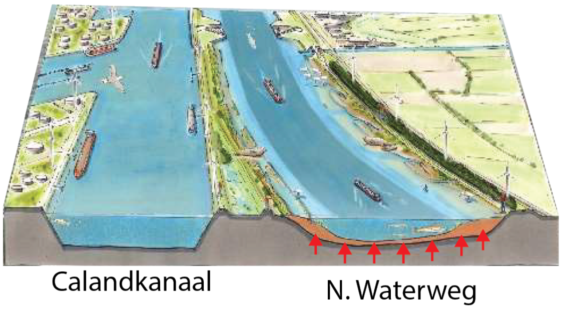

Figure 3.5: Artistic impression of shallowing of the Nieuwe Waterweg river around Maasdijk (from Meyer [2020]). The sketch shows the unaltered Calandkanaal on the left, and the modified Nieuwe Waterweg on the right. Image by Dirk Oomen en Peter Veldt (Bureau Stroming).

3.3.2. System intervention for the shallowing measure

The concept of shallowing is schematised as a uniform bed level that results from flattening out fluctuations in the reference river bed. The *bed level change* is the difference between the MBLs of the reference and intervention states. In this research, the *bed level change* is the decision variable i.e. the variable controlled by the decision-maker.

The reference bed level of the Nieuwe Waterweg and Nieuwe Maas, together with the different levels of shallowing is presented in Figure 3.6. For the section between Hoek van Holland (estuary mouth) and the Benelux tunnel, four alternative bed levels of shallowing were chosen that results in the following states:

1. Reference state: Bed level at NAP -16.4/-16.2 m (+0.0 m)
2. MBL increase of 1.4 m resulting in a bed level at NAP -15.0 m (+1.4 m)
3. MBL increase of 1.9 m resulting in a bed level at NAP -14.5 m (+1.9 m)
4. MBL increase of 2.9 m resulting in a bed level at NAP -13.5 m (+2.9 m)
5. MBL increase of 3.9 m resulting in a bed level at NAP -12.5 m (+3.9 m)

The same shallowing bed level holds for all alternatives for the section between the Benelux tunnel and the Erasmusbrug. In this case, all areas deeper than NAP -12.5 m are levelled up to this value. This choice was made to obtain an uniform bed for the higher level of shallowing (NAP -12.5 m). If this stretch were not shallowed, the bed longitudinal profile would exhibit an irregular deepened area that could bias results.

The extent of the shallowing intervention covers the area closer to the open connection with the sea, instead of an inner branch in the estuary. Interventions in this area are expected to have more effect on salt intrusion [ter Maat et al., 2014, van der Kaaij et al., 2010].

The choice for the degree of shallowing was made based on three aspects. First, it should be shaped according to the stair-steps bottom configuration of the reference state (see Figure 3.4). Secondly, it was decided to flatten out all irregularities of the current bed. Human-induced bed irregularities in the Nieuwe Waterweg are expected to affect salt transport via enhancing vertical mixing [van der Heijden, 2018, Wegman, 2021], which could lead to misleading interpretation of results if the contribution of these irregularities are significant compared to the uniform increase of the bed. Thirdly, changing the bed level impose new conditions to the design vessel's size. The higher the Maintained Bed Level (MBL), the lower the available water depth, and the smaller the design vessel. Shallowing levels were chosen to include five different fleet compositions in the traffic model. The designed MBLs with their corresponding design vessel draughts are indicated in Figure 3.6.

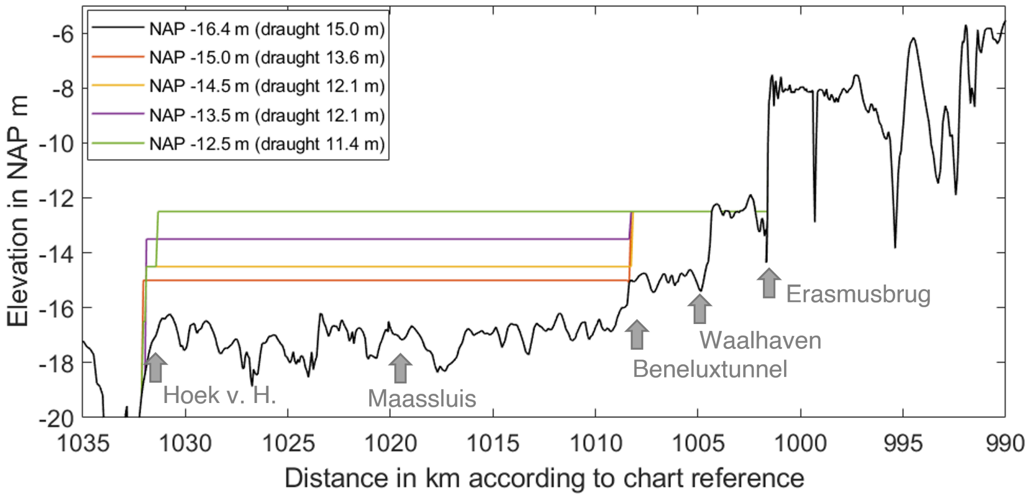

Figure 3.6: Bed levels along the Nieuwe Waterway and Nieuwe Maas for a longitudinal transect through the channel center. The reference state (black line) and shallowing bed levels (coloured lines) are depicted. Bathymetry values for the reference state (black line) were provided by the Port of Rotterdam Authority. The legend indicates the design vessel draught that corresponds to each shallowing state.

3.3.3. Objective-based assessment through FoR

This section explains how the Frame of Reference approach by van Koningsveld [2003] and the objective-based assessment of nature-based solutions by [Laboyrie et al., 2018] can be used in the context of this research. First, a single strategic objective is defined in relation to the requirements of freshwater availability and port logistic stakeholders. It should be noticed that in an actual project, the strategy should include many more values and interests at stake, such as natural habitats, water safety, and urban development.

Afterwards, the operational objectives are formulated, and performance indicators are chosen accordingly. This process is performed twice, one for each functional requirement. Then, the Quantitative State Concept is specified concerning the tools to calculate these indicators. Subsequently, the benchmark, intervention, and evaluation procedures are specified.

Formulation of the strategic objective

Guarantee fresh-water availability in the Rhine-Meuse Delta by limiting salt intrusion through the shallowing of the waterways, while enabling the port to keep a competitive position of its waterborne activities in terms of port efficiency and capacity.[3]

Operational objective for the freshwater supply function
Provide an optimal quality of the estuarine bodies of water serving the freshwater supply sub-functions of drinking, industrial, and agricultural uses. This should be achieved by maintaining the salinity concentrations below the legal standard defined by the legislation during periods of freshwater demand.

Operational objective for the port logistics function
Provide suitable hydrodynamic conditions for vessels accessibility in the waterways, port basins, and berths, preventing significant impact on port efficiency and capacity. This should be achieved by guaranteeing that waiting times are below the service level defined by the port authority. At the same time, terminal throughput should meet the service level required by the terminal operator.

Performance indicators
Then, the chosen performance indicators to be measured are:

1. ***Freshwater supply system:*** The duration in which normative salinity standards are exceeded during periods of freshwater demand. From now on, this is called *salinisation days*. As an assumption, the desired state is achieved when salinisation days are cut down to zero. Furthermore, it is assumed there is always freshwater demand, and external water storage sources are not available.

2. ***Port efficiency:*** Time-averaged total waiting time (*hs*). The limit value of this indicator is specified according to the service level defined by the port authority. The maximum waiting time is estimated in 11 hs.[4]

3. ***Port capacity:*** Terminal throughput (*m3 per unit of time*). This study assumes that the terminal wishes to sustain the same throughput compared to a reference state. The exact value of the reference throughput is determined in the modelling study.

Quantitative State Concept for the assessment of freshwater supply performance
The duration in which the normative hourly chloride content is exceeded has to be determined. Variations of salinity are expressed in chloride concentration (g/l or mg/l). Due to the technological resources available for this research, a numerical modelling study is preferred over a physical modelling study to perform the calculations. The model should be suitable to investigate the effect of bathymetry changes on water and salt transport in the estuary. After evaluating different 1D, 2DH, 3D, and analytical models available, a 3D model approach was chosen to be the most suitable to model large scales changes in the bathymetry. The 3D model selected achieves results time-efficiently with a much larger accuracy than 1D, 2DH, and analytical models. This choice is further substantiated in Section B.0.1. In the Rhine-Meuse Delta, one of the best tools available for salinisation studies is the 3D *Operational Flow Model Rotterdam (OSR)* [Kranenburg, 2015]. This is a model schematisation developed by the Port of Rotterdam Authority that runs using the SIMONA software [Rijkswaterstaat]. The software is owned by the Rijkswaterstaat and managed by Deltares.

Reference locations at Boerengat and Brienenoordbrug are defined at reference water inlets as described in Section 3.2. A time series of the chloride concentration is obtained for the simulation period. The indicator *salinisation days* is obtained by computing the total duration in which chloride content is above the specified legal limit at these locations.

Quantitative State Concept for the assessment of port logistics performance
Likewise, the quantification approach for port efficiency and capacity is based on a numerical modelling study. For this research, the software *OpenTNSim* or *Open-source Transport Network Simulation* developed by the Faculty of Civil Engineering of TU Delft was chosen [Van Koningsveld and Den Uijl,

[3] Other aspects, such as port sustainability and safety, are left out of the scope of this research.

[4] A typical cycle of a liquid bulk vessel is estimated to last 48 hs [PIANC, 2016]. The service time for a liquid bulk vessel in the Port of Rotterdam is assumed to last between 15 hs to 18 hs [Arcadis, 2015]. The inbound and outbound sailing time is estimated at 16.4 hs based on an average vessel speed of 4.5 m/s. Then, to fulfil the 48 hs requirement for one cycle, the maximum waiting time is set in 11 hs.

2020]. The choice is based on three main reasons [van Koningsveld et al., 2021]: (1) the model can investigate mesoscopic traffic behaviour, (2) it is suitable for studying capacity-related consequences of different traffic scenarios and network configurations, and (3) it can be used to couple traffic simulations with hydrodynamic data, such as the outcomes from the OSR-model.

Moreover, a script was recently developed by the Ports & Waterways staff of TU Delft, which is suitable to quantify the effect of changes in open estuaries hydrodynamics on waterborne port logistics. Outcomes of this model include, amongst other parameters, the average waiting time over the entire simulation and the list with all ships calling at a specific terminal in the port. Then, the throughput can be obtained by adding up the parcel size of all the vessels served at a specific terminal.

Benchmark and intervention procedures
The indicator for the current state is evaluated against the desired state. If the desired state is not achieved for either operational objectives, the decision-maker can manipulate the system by changing the river bed level.

First, the assessment of freshwater supply performance is done by measuring the current state through the indicator *salinisation days*. Then, it is verified whether it reaches the target of zero days. Secondly, for port logistics, the indicator *average waiting time* is used to check whether it is below the specified service level of 11 hs. Also, if the throughput is constant for all the modelled states.

Evaluation procedure
The steps above are evaluated against both operational objectives and the strategic objectives. This specific step is part of the discussion (Chapter5).

3.3.4. Prediction of impact on water and salt transport

The assessment of effects requires numerical modelling predictions of water and salt transport in the estuary. This section describes the main steps and choices followed for the study with the OSR model.

Overall steps of the OSR model

The OSR model system consists of two sub-models: the 2DH OSR-Haven model and the 3D OSR-NSC model. The model version used in this study is the OSR-Haven-2020-v101 and OSR-NSC-2020-v101 (Grof).

An overview of the stages to conduct the modelling study is presented in the upper right part of Figure 3.8. In the first stage, 2D boundary conditions are gathered. These conditions include water levels, current velocities, and salinity at the North Sea edges and river discharges and salinity at the Lek, Waal, and Maas river edges. Also, the initial conditions. Besides, the model schematisation includes all hydraulic structures and the river bathymetry. The latter is further explained in the following subsection.

Secondly, in a concept known as nesting, the 2DH model is run to derive the 3D boundary conditions imposed to the 3D model. This model is spatially smaller than the 2DH model, as shown in Figure 3.7. The boundary conditions in the nested model concern the time series for the Riemann conditions on the sea edges discharges through the edges of rivers, and salinity at both the sea and river edges. These are defined over the water column with a vertical spatial resolution of 10 layers. After the 3D boundary conditions are obtained, the 3D OSR-NSC Grof is used to solve the water and salt transport in the domain.

Finally, model outcomes concerning water levels, flow velocities, and salinity inside the domain can be exported in different formats to produce new results. This research focuses on salinity variations at Boerengat and Brienenoord, the two study locations on the Nieuwe Maas River.

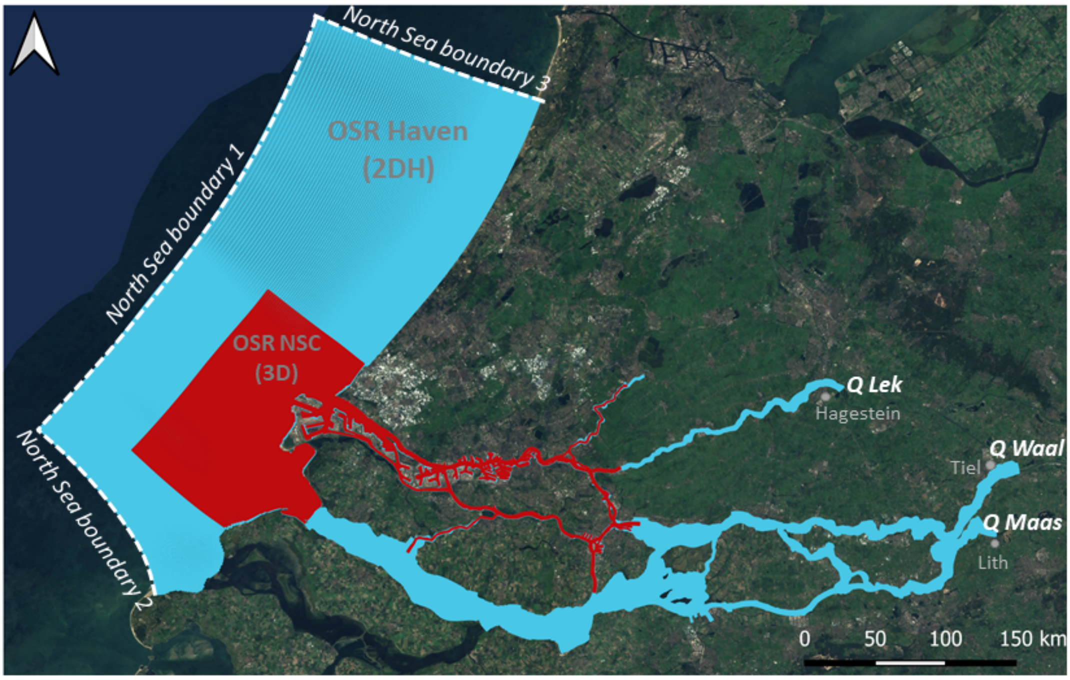

Figure 3.7: Boundary conditions of the OSR model. The 2DH OSR Haven model (cyan colour) nests the 3D OSR NSC model (red colour). Conditions are imposed at three sea boundaries and three river boundaries, from which the new boundary conditions for the 3D model are derived. Bathymetry changes are implemented to both models.

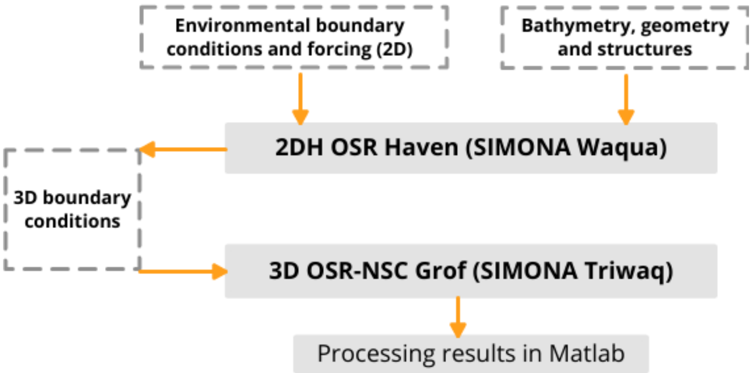

Figure 3.8: Overview of the structure of the OSR model.

Boundary conditions, initial conditions and model set-up

One specific type of salinisation event is modelled. It manifests as a prolonged period of low river discharge (Q < 1000 m3/sec at Lobith), and mild wind conditions, i.e. without wind set-up. Such an event can last for several weeks [de Vries, 2014]. Also, the simulation time should at least include one complete spring-neap tidal period (~ 29.5 days) to address the effect of the spring-neap forcing on salinity. Seasonal variations of river discharge are not considered in this modelling study, and it is assumed that discharge at Lobith is 1000 m3/sec during the entire simulation. The discharge measured at Lobith can be related to the proportions at rivers Lek, Waal, and Maas. It results in flow rates of 159 m3/sec, 697 m3/sec, and 169 m3/sec, respectively.[5] In such conditions, river run-off leaves the system almost entirely through the Nieuwe Waterweg, while the Haringvliet sluices remain closed [ter Maat, 2015].

Also, the model includes the operation of other open boundary conditions that are important for flow

[5]Values derived from 2000-2019 time series of average monthly discharges for each river, obtained from the Asset Management Department of the Port of Rotterdam Authority.

and salt transport. These include other river sections at: Dordtsche Kil, Spui South, Ben. Merwede, and Moerdijk bridge. The OSR includes all relevant hydraulic structures for flow regulation, flood safety, and shipping as internal boundaries (see also Table B.3). It is important to mention that salinity is controlled by the operation of the Haringvliet sluices, the Hagesteijn weir and the Volkerak sluices. The most important one is the Haringvliet dam, which closes off the Haringvliet river when discharge measured at Lobith is below 1100 m3/sec [Huismans et al., 2018].

Also, the initial variables that need to be know at the start of the simulation are the horizontal flow velocity, water levels, and salinity. In all simulations, initial conditions corresponded to the state on the 1st of January of 2021.

Finally, a simulation period from 12/05/2014 until 08/07/2014 was chosen, using an initial spin-up period from 12/05/2014 to 26/05/2014 (spin-up of 14 days + simulation of 42 days). Tidal boundary conditions from measurements were included at the north sea boundaries. In this period, wind speeds are below 10 m/s, which can be associated to mild conditions (for more details, see also Figure B.7). Consequently, wind set-up is negligible for most of the simulation (see Figure 3.9).

For more information about the model set-up, the reader is referred to Appendix B.

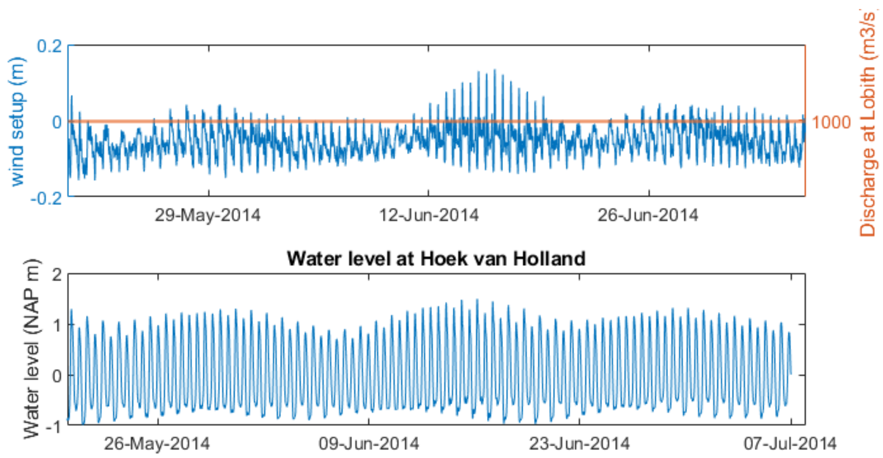

Figure 3.9: Boundary conditions in the OSR-model. The upper figure shows wind set-up estimated at Hoek van Holland (blue) and river discharge at Lobith (orange). Here, wind set-up was estimated by subtracting the astronomical tide from the measured water level. It is seen that wind set-up is generally below 0.1 m, except for a period of 3 days (identified from 14-06 to 17-06) in which it reaches 0.14 m. This brief period is associated with a northerly wind of around 10 m/s (see also Figure B.7). The bottom figure presents water levels measured at Hoek van Holland (data from Rijskwaterstaat).

Reference bathymetry and shallowing

For the reference state, it was chosen to work with the latest schematisation provided by the Port of Rotterdam. It includes the execution of Maasvlakte 2, the Nieuwe Waterweg deepening, and adjustments to the Breediep and the Botlek have been incorporated.

As presented in Section 3.3.2, four levels of shallowing are proposed. The shallowing measure is schematised by increasing bed in all grid cells below the target level. In general, the bed adjustment follows the stair-steps bottom configuration of the reference state. Locally, at the bed stair-steps, the mouth, and river junctions, the transition from shallowed to non-shallowed was gradually built, keeping the original slope. By means of an example, Figures 3.10 and 3.11 show the situations pre-and-post the + 1.9 m shallowing state. For the remaining bathymetry maps, the reader is referred to Section B.0.2.

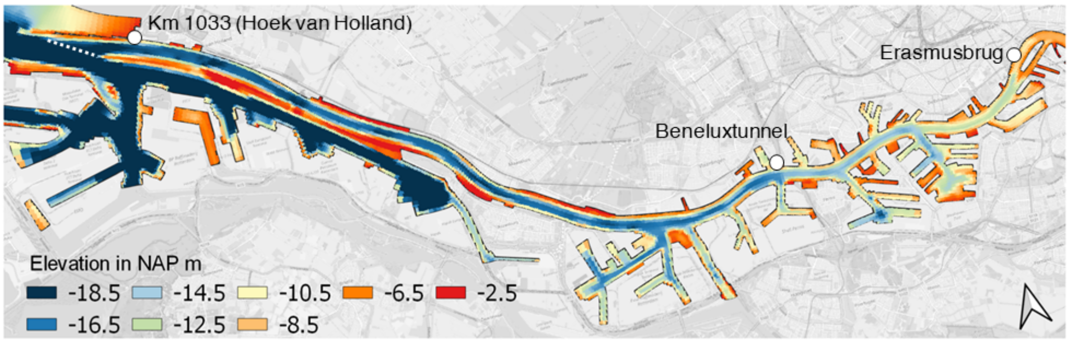

Figure 3.10: Bathymetry map for the reference state. All areas deeper than NAP -18 m are depicted in dark blue. As seen from this figure, the actual depth of the river section between Hoek van Holland and the Beneluxtunnel is generally between NAP -16 m and NAP -18 m.

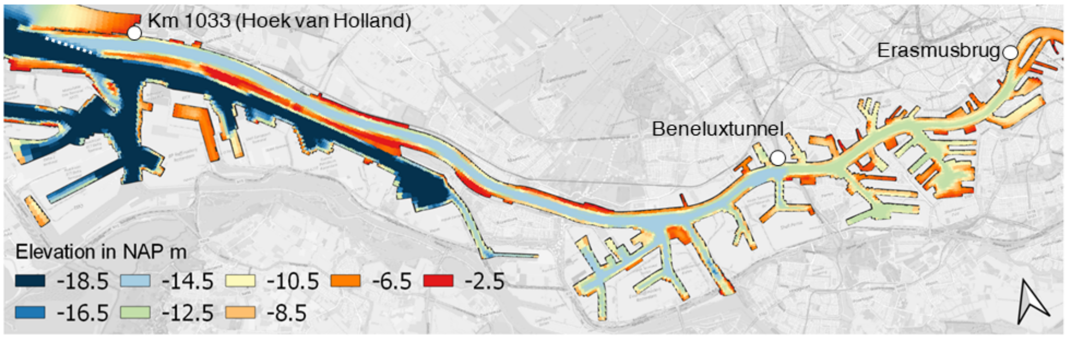

Figure 3.11: Bathymetry maps for one the shallowing state NAP -14.5 m (1.9 m of bed level increase). The colour bar of this figure was adjusted so that shallowed areas can easily be viewed in dark blue. These are the areas deeper than NAP -14.5 m. Also, the areas between Beneluxtunnel and the Erasmusbrug are shallowed up to NAP -14.5 m. The remaining areas are not intervened. The seaward edge of the shallowing is at Hoek van Holland (dashed white line) and the landward edge is at the Erasmusbrug. Most of the shallowing takes place between Hoek van Holland and the Beneluxtunnel. Additional areas are shallowed in the main waterway and harbour basins in the Waalhaven and Eemhaven.

3.3.5. Prediction of impact on port efficiency and capacity

This section describes the steps followed and assumptions made to conduct the modelling study on waterborne port logistics using the OpenTNSim model, a Python package developed by TU Delft. OpenTNSim contains a library to specify agents and several tools to analyse network behaviour [van Koningsveld et al., 2021]. Also, it can be used to couple traffic simulations with 2DH hydrodynamic data. In this research, the coupling was done with the hydrodynamic output from the OSR-model along the waterways of the Port of Rotterdam (Section 3.3.4).

First, the different elements in the system and the interaction between them need to be clearly defined. The following choices were made to simplify the system:

- Only shipping operations towards the Koole terminal are considered. It means that the interactions with shipping in the seaward accesses to Maasvlakte 1 - 2, and Europoort are removed from the analysis. The same simplification holds for interactions with vessels calling at all other inland seaports terminals.

- Only seagoing vessels from the North Sea are considered. It implies that traffic to the hinterland through inland waterways is not considered, including the IWT traffic to/from the Koole terminal. The shallowing interventions do not challenge the required water depth of the design inland vessel, which is 4.4 m.[6]. Hence, it is assumed that the contribution of inland transport to the network capacity would not be significantly affected. Then, it would be more interesting to study the effect on larger (seagoing) vessels that can be affected by a decrease in the available water depth.

[6]Value calculated by following the Port of Rotterdam policy. FWA = 0.10 m; UKC = 0.39 m; Vessel draught = 3.94 m for a vessel class 'VIa' according to the CEMT classification.

- Terminal operations include only import of cargo. Loaded vessels sail into the terminal, and unloaded vessels sail back to the sea.

Furthermore, the modelling study was conducted according to the following stages:

1. Build a one-dimensional traffic network. This step includes the bathymetry of the nautical infrastructure for the reference and shallowing states.
2. Outline general choices and assumptions made to simplify vessels nautical behaviour and the network infrastructure.
3. Define the fleet composition by choosing different vessel classes. This step involves all relevant vessel properties for the modelling study.
4. Decide upon the necessary aspects related to the arrival process, including the arrival rate (or inter-arrival time) of vessels.
5. Import hydrodynamic data derived from the OSR model (water levels and flow velocity time series). From this input, the model can calculate tidal windows.
6. Choose a simulation duration based on relevant criteria. Also, estimate the number of simulation runs depending on the expected accuracy.

The following subsections elaborate on each one of these steps.

1- Traffic network

The traffic network is mainly a route with the starting point at the North Sea and the destination at the Koole terminal. Also, there are two anchorage areas. The network consists of a total of 21 nodes and 20 edges[7] (see Figure 3.12). Also, every node has latitude, longitude coordinates and a bed elevation to refer to the model. Some points have specific properties related to the nautical infrastructure and the port processes defined there: (a) arrival and departure at the network origin; (b) manoeuvring at the turning basins; (c) manoeuvring and (de)berthing at the destination terminal; (d) waiting at anchorage areas.

For detailed information about the network properties, the reader is referred to Section C.1.

[7] Edges are lines linking two consecutive nodes

Figure 3.12: Port and waterways system network, boundaries and components. The route is depicted in blue, with green dots representing nodes. Turning basins in the lower right map are depicted in blue dashed line. The purple area in the lower-left map represents the 3rd Petroleum Haven area, whereas the lower right map represents the Koole liquid bulk terminal.

Maintained Bed Level

A total of seven states (reference and shallowing states) are modelled. These states correspond to the ones indicated in Section 3.3.2 plus two more states (shallowing of NAP -13.1 m/ +3.3 m and NAP -12.8 m/ +3.6 m) that were added to increase the reliability of results. The bed position in the network is defined by the Maintained Bed Level (MBL) with respect to NAP, defined according to the official chart of port [Port of Rotterdam Authority, 2021]. For the nodes along the entrance channel in the North Sea, it is assumed that vessels are not affected by the bottom. Hence, a value of MBL of NAP -50 m was chosen. All vessels follow the entrance channel. In reality, only the vessels with the largest draughts are obliged to follow this route. For detailed information about the MBL value in each node of the network, the reader is referred to Section C.1.

2- Vessels nautical behaviour

A theoretical description of the overall vessel navigational behaviour was presented in Section 2.7. To represent vessels nautical behaviour, certain assumptions are made to simplify the network. First, certain choices about the infrastructure design are made:

- The destination is fixed to the Koole terminal.
- Vessel movements between nodes are modelled in 1D.
- Vessels are allowed when, within their required sailing time, three conditions are met: berth availability, sufficient water depth during the entire journey, and sufficiently low cross-current velocities at a controlling point in the harbour basin entrance.
- The model considers a First Come First Serve (FCFS) queue discipline to determine who is served next.
- Certain characteristics and rules apply to the nautical infrastructure. Vessels can wait only at the two anchorage areas. Each one of these anchorage has a maximum capacity of 25 vessels. Manoeuvring in the turning basin and during the berthing procedure occurs over a deterministic time interval. Also, waterways in the model are mainly designed for two-way traffic. Only a one-way part is included in the 3e Petroleumhaven, between the Nieuwe Waterweg and the terminal.

- Anchorage areas are schematised as nodes with a maximum vessel capacity. Vessels wait in the anchorage areas closest to the harbour entrance if a spot is available. Other routines of ship allocation and manoeuvring within the anchorage area are not considered.

- Berths are schematised as nodes. The model allows choosing between two types of berths: jetty or quay. However, the model does not distinguish that different berths can have different accessibility conditions (e.g. MBLs defined for every berth).

- The model does not distinguish terminal and berth operations. Then, the service time is the sum of (un)loading time and (un)mooring time.

- Vessels have a fixed speed equal to 4.5 m/s (value based on de Jong [2020]).

- Traffic rules: The model considers a minimum headway with predecessors. It means that vessels need to keep a minimum distance between them. Rules about encountering, speed reduction, crossing priorities, and overtaking are not considered.

- The model considers an unlimited number of tugs and pilots.

- Weather conditions are not included.

- The effect of water safety structures is not included in the model. This choice is not expected to influence the results since simulations are not carried out for extreme high waters.

Other important assumptions about the navigational behaviour of vessels are to be mentioned. These are related to the fleet composition, the arrival process, and the tidal windows. The three of them are described below.

3- Fleet composition

The model can consider different types of vessels. First, assumptions are made based on typical tankers calling at a liquid bulk terminal. Six typical tankers were selected based, ranging from an LR2 tanker to coaster tankers [United States. Bureau of Transportation Statistics, 2020]. Two other small coasters were added to this list since it was found that the Koole terminal offers this type of maritime shipping service (see also www.koole.com). Then, vessel classes were fit to an empirical distribution based on the information provided by the work of de Jong [2020] for the Koole terminal. The fleet size distribution is depicted in Figure 3.13. For more information about the vessel properties, the reader is referred to Section C.1.

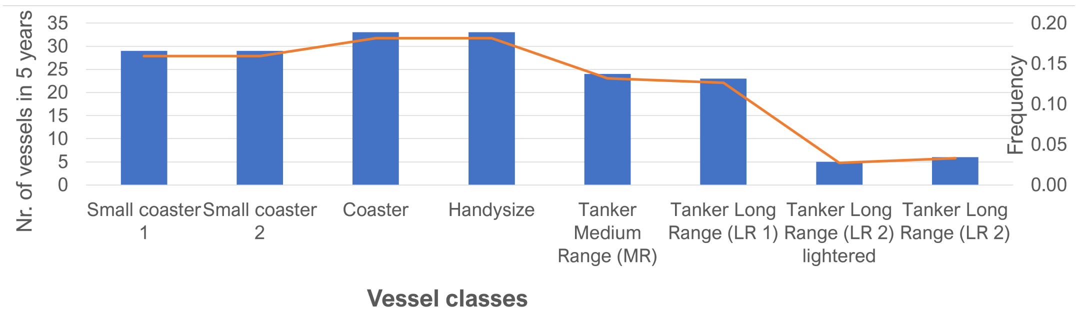

Figure 3.13: Fleet size distribution assumed for the Koole terminal in the 3rd Petroleum Haven. The x-axis shows the vessel classes used in the modelling study. The y-axis on the left shows arrivals at the Koole terminal between January 2015 and February 2020 from de Jong [2020]. The number of vessels for coasters and small coasters was assumed. The y-axis on the right and the orange line present the relative frequency of arrivals, based on the number of arrivals.

Criteria for the accessibility of vessels

As mentioned in Subsection 3.3.2, the fleet composition is bounded to the chosen shallowing levels. According to the Port of Rotterdam policy, accessibility should be provided for 99% of the tidal cycles (often during high tides) for tide-bound vessels and 99% of the time for non-tide-bound vessels [de Jong, 2020]. Then, only the vessels that can comply with this rule are included in the simulation. Access to the port is possible for the 8 vessels in the list for the reference state. However, shallowing prohibits access to the largest vessels, leaving one or more vessel classes out (see Table 3.1). The estimation of the accessibility conditions for each vessel class is based on Equation 2.3 in Section 2.7.5, which considers vertical tidal windows, but not horizontal.

Table 3.1: Accessibility conditions of vertical tidal windows based on the Port of Rotterdam policy. The table show the criteria used for the different vessel classes in the modelling study. When vessels do not need a vertical tidal window to access, they are labelled as 'Non-tide bounded (NTB)'. When the accessibility is less than 99%, vessels do not comply with the port policy and cannot access the port. These cases are labelled as 'No access (NA)'. When vessels can access during a tidal window during at least 99% of the high waters, they are 'Tide bounded (TB)'. The information in this table required an estimation of the minimum required tidal water level (in w.r.t. NAP), which was calculated with Equation 2.3 assuming a $\Delta H = 0.15m$ and $HW_{99\%} = 0.48m$. Finally, the last row shows the resulting fleet composition as the sum of vessel classes that comply with the criteria.

MBL (NAP m)	-16.4	-15.0	-14.5	-13.5	-13.1	-12.8	-12.5
Bed level change	0 m	1.4 m	1.9 m	2.9 m	3.3 m	3.6 m	3.9 m
Small coaster 1	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Small coaster 2	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Coaster	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Handy Size	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Medium Range	NTB	NTB	NTB	NTB	NTB	NTB	TB
Long Range 1	NTB	NTB	NTB	TB	TB	NA	NA
Long Range 2 (p.l.)[1]	NTB	TB	NA	NA	NA	NA	NA
Long Range 2	TB	NA	NA	NA	NA	NA	NA
Fleet composition (# of classes)	8	7	6	6	6	5	5

[1] Partially loaded vessel.

4- Vessel arrival and service processes

The OpenTNSim model allows different arrival stochastic distributions according to a random process, such as uniform, Erlang-k, or negative exponential distribution (NED). However, due to certain limitations of the model developed for this case study, only the uniform distribution can be chosen. Hence, a constant value of the arrival rate is applied during the simulation. For the reference state, the final value of the arrival rate was found by running the model with different values until achieving a terminal occupancy of 0.4. This is a suitable value of occupancy in liquid bulk terminals [van Koningsveld et al., 2021].

It was already mentioned that shallowing imposes accessibility restrictions on the largest vessels. Here, it is assumed that the shipping company compensates for the missing vessels by increasing the arrival rate of the vessels that can access the port. In doing so, the terminal can keep up with the same throughput obtained for the reference state. As a side effect, the traffic in the port is expected to increase significantly. For more details about the arrival process and throughput calculation for each simulation, the reader is referred to Section C.1.

Besides, service times for this case study follow the same values used in the traffic studies for the deepening of the Nieuwe Waterweg and Botlek area [Arcadis, 2015]. The service time varies between 15 hs and 18 hs (for more details, see also Section C.1).

5- Tidal windows calculation

The model developed for this case study considers tidal water levels and velocities as external conditions. First, water level and velocity data over a spring-neap tidal cycle are derived from the OSR model (Section 3.3.4). Then, the model calculates the tidal windows for tide-bounded vessels, as explained below (see also an overview structure of this calculation in Figure 3.14):

- Vertical tidal windows (water level restriction): Water level data sets are loaded at each of the 21 nodes in the network. At each node, the model computes the available water depth experienced by the vessel at every step of the route. In addition, the model also computes the required water depth at every location based on the vessel properties (FWA and UKC). This way, vessels know the port accessibility conditions upfront and decide whether to sail towards the terminal if sufficient time is available to navigate through the waterway and turning basins, (de)berth, and (un)load cargo. If this is not feasible, vessels wait until a time window is made available.

- Horizontal tidal windows (cross-currents restriction): Current tidal restrictions apply in cases where the manoeuvrability of vessels is compromised at some location. To compute the horizontal tidal window, the model compares the velocity at Node Nr. 15 (near the entrance of the harbour basin) against the critical cross-current velocity. The latter is estimated at 0.5 m/s, assuming tug and pilot assistance can fasten and lead vessels in such conditions. This condition is an estimation because the policy of the PoR could not yet be included in the model.

More information about the water level and velocity signals used in the model can be found in Section C.1.

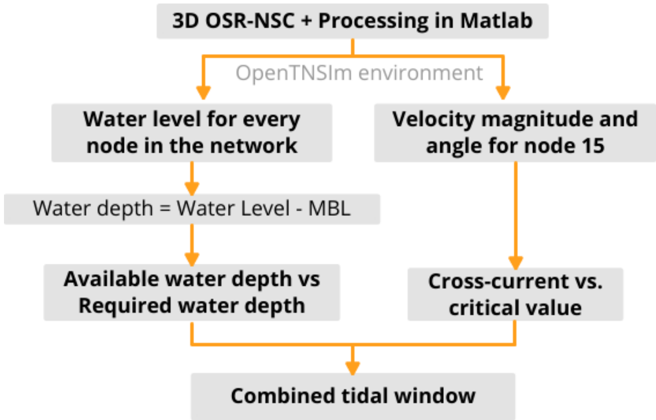

Figure 3.14: Overview structure of the tidal window calculation (see also Appendix C) for an exemplar illustration of the calculation.

6- Choice of the simulation period and number of runs

Model simulations have a duration of 174.6 days (~ 6 months and precisely six complete spring-tidal cycles), and an initial spin-up time of 5.8 days. The latter is chosen by running the model and observing a stable berth occupation at the terminal. For simplicity, the total duration is determined based on ‘n’ repetitions of the spring-tidal cycle because an essential input for this model is the hydrodynamic data derived from the OSR model. For this case, it was observed that computational effort increases significantly for more than six spring-tidal cycles, without a significant improvement in the accuracy.

Since the arrival of vessels at the port is simulated as a random process, every run executed with a different seed (i.e. the initial value of the random sequence) would lead to different results. Therefore, a certain number of repetitions is required to acquire reliable outcomes. The number of runs is defined according to the desired accuracy and the standard deviation [Groenveld, 2001]:

$$N = \frac{\left(\sigma \cdot Z_{\alpha/2}\right)^2}{d^2} \tag{3.1}$$

With:
N: Number of runs; σ: Standard Deviation; $Z_{\alpha/2}$: Two-tailed Z-score for a level of confidence 1-α; d: Accuracy.

The average waiting time is chosen as the variable to estimate the number of runs and the model uncertainty. More details about the results of this calculation can be found in Section C.2.

3.3.6. Performance indicators quantification

This section presents the calculation methodology of the performance indicators. This is done in two parts, one for each type of indicator.

Relation between bed level change and salinisation days
Outcomes from the OSR model consist of time-series of the salinity (in PSU) at the Boerengat inlet and Brienenoordbrug. The model is solved for a 10-sigma-layer vertical grid, which results can be obtained for 11 water depth values distributed over the water column. The time series used to quantify the performance of water inlets is obtained for a water depth of NAP -2.50m, which coincides approximately with the 4th layer of the grid (from top to bottom, at 46% of the water depth). Results are processed in a Matlab script to determine the duration in which the chloride content exceeds the legal standard. The duration is calculated for the 150 -Cl mg/l and 400 -Cl mg/l standards[8], and over the simulation period of 42 days.

Then, for each of the five states simulated in the OSR model, an equal amount of values of *salinisation days* is obtained. Afterwards, the decision variable *bed level change* is related to the indicator by finding a numerical interpolation with the Curve Fitting Toolbox developed by MatLab [MATLAB, 2020]. The exact process is repeated for the two locations, Boerengat and Brienenoord. For each location, mathematical functions are found for the drinking and agricultural end-users. That makes a total of four relations.

Relation between bed level change and waiting times and throughput
The model in OpenTNSim directly computes the waiting time of each vessel in the simulation and the average waiting time over the simulation time. Due to the stochastic character of the average waiting time, the indicator is estimated as the mean value over a set of 10 to 15 runs. The OpenTNSim also provides the list of vessels served at the Koole terminal. The sum of the parcel size for all vessels in the total amount of cargo handled during the simulation time, i.e. the terminal throughput. As indicated in Section 3.3.5, the terminal throughput computed for the reference state is kept equal for all the states. Simulations are run for different arrival rates so that the reference targeted throughput can be achieved. Then, the most important outcome is the *average waiting time* for each state. In other words, only waiting times are treated as a variable, meaning that a quantitative assessment of changes is possible in terms of port efficiency but not in terms of port capacity.

Finally, a relation is obtained between *bed level change* and the *average waiting time*. Similarly, data is fitted with a function using the Curve Fitting Toolbox. In this case, the curve is fitted to a total of seven values.

3.3.7. Quantitative trade-offs between freshwater supply and port logistics
The last step of the comparison tool relates the two fitting functions obtained in Section 3.3.6. This way, the *salinisation days* can be traded off against the *average waiting time* by the inherent decision variable *bed level change*. Finally, graphs are built representing the three variables, with *salinisation days* in the x-axis, *average waiting time* in the y-axis, and the *bed level change* as a coloured scale bar.

There are four individual mathematical relations for the freshwater supply end-users which are compared to one single mathematical relation for port efficiency. Thus, four trade-off graphs are possible.

[8] The first value is related to drinking and industrial use, and the second one is to agricultural use. In reality, the standard for the Boerengat water inlet is set at 400 -Cl mg/l. However, an analysis based on the 150 -Cl mg/l was added to observe the sensibility in the final results.

4

Results

This chapter is set out to present the results obtained from implementing the tool for the case study of the shallowing of the Rotterdam Waterways. The chapter is divided into four sections. First, Section 4.1 presents an overview of the impact of shallowing on water and salt transport. Secondly, Section 4.2 presents findings on the implications for freshwater supply. Thirdly, Section 4.3 is set out to describe results on implications for port efficiency. Fourthly, Section 4.4 present the resulting quantitative trade-offs.

4.1. Impact on water and salt transport

The OSR model was employed to conduct simulations for a salinisation event with low river discharge and mild wind climate. Four different levels of shallowing were modelled, besides the reference case.

4.1.1. Impact on the hydrodynamics

A few interesting results from the modelling study concern the effects of shallowing on the tidal range, water depth, tidal flow rates, and flow velocities over the spring-neap tidal cycle. For the reference state, spring tides at Hoek van Holland vary approximately between NAP + 1.3 to NAP -0.80 m (range of ∼ 2.1 m), and neap tides vary approximately between NAP + 0.70 to NAP -0.65 m (range of ∼ 1.4 m). In general, results show that the spring tidal range shortens between 0.20 - 0.30 m. During neap, it shortens between 0.05 - 0.10 m. The mean water level for the shallowing states is nearly equal to the reference state (less than 0.02 m difference) for the entire simulation (see also Figures B.10 to B.12). Consequently, the increase in bed level after shallowing is almost equal to the decrease in water depth.

Also, the amplitude of the tidal flow rates decreases for shallowing levels. The latter was computed with the OSR model at three controlling stations at the Nieuwe Waterweg (km-1017), Nieuwe Maas (km 995), and Oude Maas (km 997). For the Nieuwe Waterweg, flow rate amplitudes decrease between 1000 m3/s to 1500 m3/s for a shallowing level of + 3.9 m. This decrease means around 10 % of the reference flow rate amplitude (see also Figures B.13 and B.15).

Finally, changes in flow velocities are relevant for the analysis of horizontal tidal windows measured along the Nieuwe Waterweg, near the entrance of the 3e Petroleumhaven. At this location, results show that shallowing leads to an increase of the moving average flow velocity of ∼ 0.15 m/s (spring tide) to ∼ 0.10 m/s (neap tide). Also, velocity angles does not change significantly. For more details about these findings, the reader is referred to Figures C.4 to C.6.

4.1.2. Impact on salt intrusion

Firstly, to understand how shallowing affects salt intrusion, the longitudinal variation of salinity during high water slack (HWS) was obtained (Figure 4.2). These results were obtained during neap tide, which corresponds to a typical high value of the salt intrusion length in the simulation. It is computed at 46% of

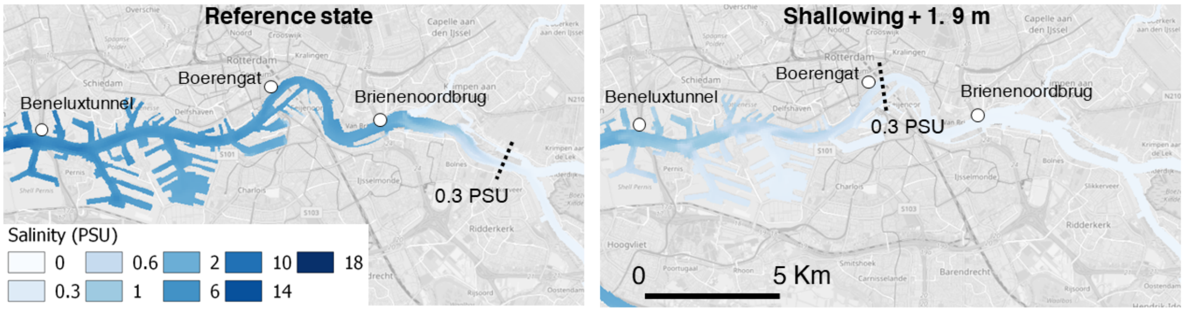

Figure 4.1: Salinity map along the Nieuwe Maas in proximity to Boerengat and Brienenoord. Results on salinity (in PSU) were obtained from the OSR-model at 46% of the water depth, which can be assumed to be the water suction depth at water inlets in this section of the river. The figure presents the outcome for the reference state (+ 0.0 m) on the left, and for the highest shallowing level (+3.9 m) on the right. The degree of salinity (in PSU) is depicted in blue color coding. The darker the blue colour, the higher the salinity. Also, the most landward position of the 0.3 PSU isohaline is depicted in black dashed line. This value equals a chloride concentrations of 165 mg/l, which is almost the legal standard used for drinking water supply. From comparing the two plots, it is seen the 0.3 PSU isohaline retreats around 10 km after shallowing, from Slikkerveer to slightly upstream of Boerengat.

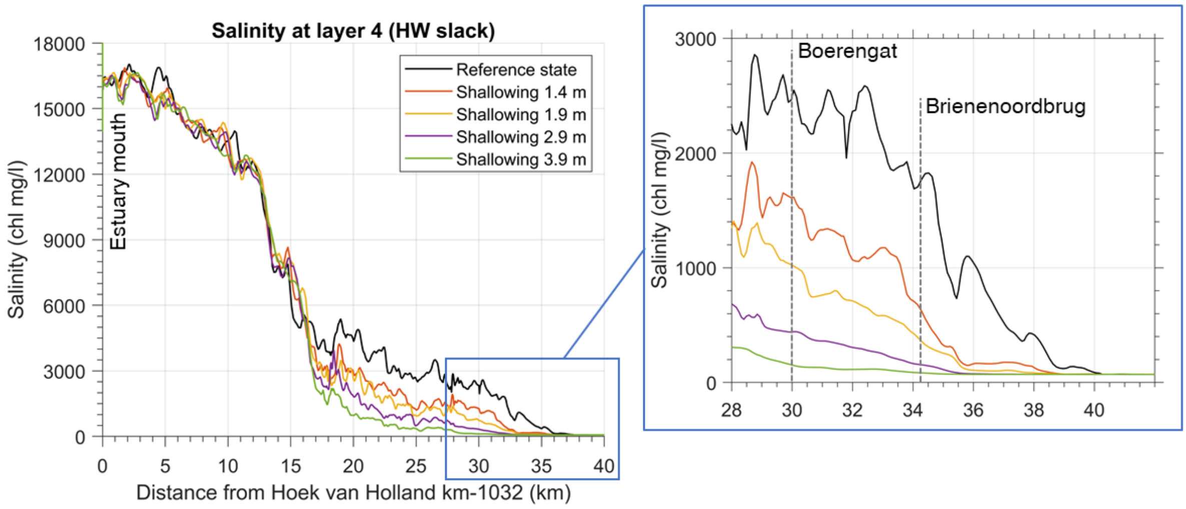

Figure 4.2: Chloride content along the Nieuwe Waterweg and Nieuwe Maas, during high slack water and neap tide. The figure shows longitudinal salinity variation on the 24-06 at 16 hs. The longitudinal transect crosses through the centre of the river cross-section at 46% of the water depth (around NAP -2.5 m, and assumed to be the water suction depth). Although it is not the most extreme case in the simulation, this situation corresponds to a typical salinity peak during low mixing conditions.

the water depth, assuming this is the water suction depth of water inlets. Results for the reference case indicates that HWS-salinity diminishes completely at 40 km from the estuary mouth, where it equals the background river salinity of 70 ch- mg/l (Figure 4.2). Also, these findings reveals that HWS-salinity is affected only in the most landward 20 - 22 kilometers of the salt-fresh water mixing length. Closer to the mouth, shallowing seems to have a limited effect (see Figure 4.2).

Compared to the reference, the 70 mg/l HWS-isohaline retreats 1.2 km (3%) for the shallowing of 1.4 m. It can retreat up to 5.5 km (14%) for the shallowing of 3.9 m. The retreat can be more significant for higher thresholds of chloride content. The 150 mg/l HWS-isohaline, which is commonly used as drinking water standard, retreats between 3 km (8%) and 10 km (26%), as seen from Figure 4.1.

Also, a closer inspection of the longitudinal variation of salinity shows a significant decrease in the mid-depth salinity for the water inlet at Boerengat (right plot in Figure 4.2). It decreases from a reference value of ~ 2600 mg/l to 160 mg/l (97% reduction) for the Shallowing of 3.9 m. Likewise, the decrease in salinity at Brienennordbrug goes from a reference of ~ 1800 mg/l to practically the river background salinity of 70 mg/l (100% reduction).

Chloride content variation at water inlets

Secondly, to provide a better insight into the effect of shallowing on specific study locations, time series of chloride content were obtained at Boerengat and Brienenoord at 46% of the water depth (Figures 4.3 and 4.4). In general, findings indicate that salinity variations at Boerengat seems to decrease significantly for the shallowing states. These salinity signals can be compared against the normative values used for agricultural and drinking water use. The first two shallowing levels have a limited effect on the salinity below the 150 mg/l threshold (up to Δ =1.9 m), whereas the third and fourth levels have a more visible effect. Instead, the first shallowing level has a limited effect on salinity below the 400 mg/l threshold but this effect is more visible for the highest three shallowing states. In the case of salinity variations at Brienenoordbrug, significant changes below the 150 mg/l are visible for the third and fourth shallowing state (from Δ =2.9 m). For the second, third, and fourth states, salinity at the water inlet is generally below the 400 mg/l threshold.

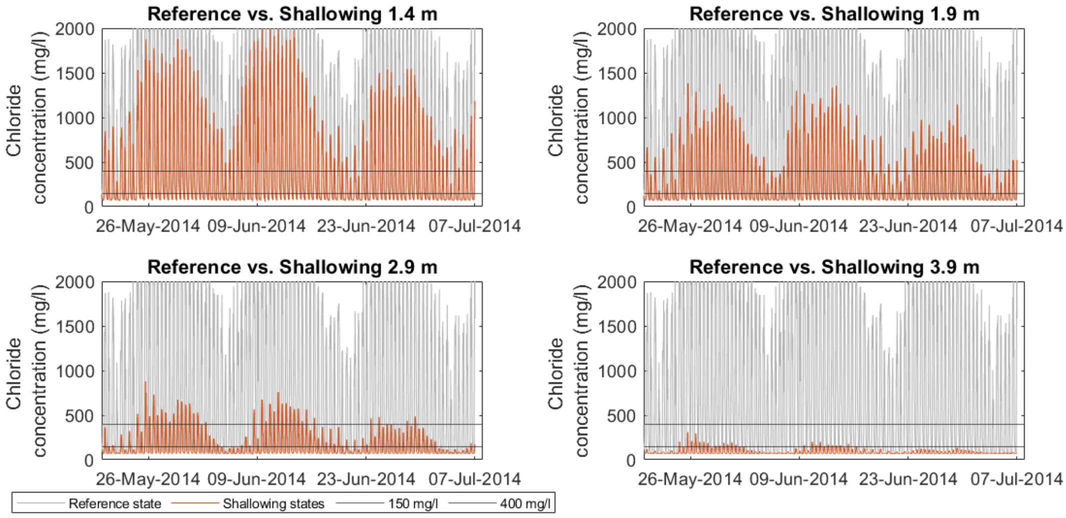

Figure 4.3: Impact of shallowing on the chloride concentration at the Boerengat water inlet. The figure presents the salinity time series at the water inlet for the reference case (grey lines in the background) and the shallowing states (orange lines). The two horizontal lines correspond to the 150 mg/l and 400 mg/l thresholds for drinking and agricultural water use, respectively.

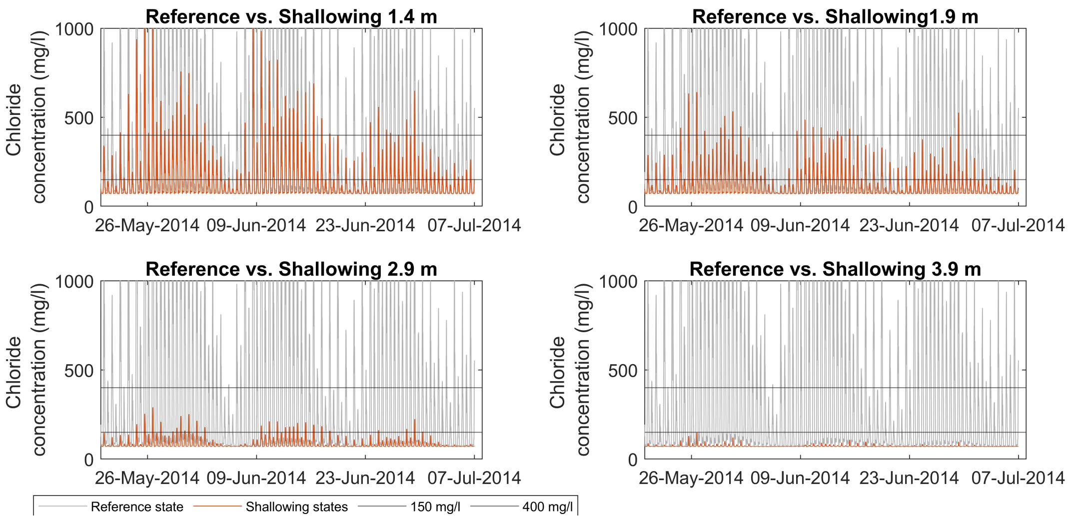

Figure 4.4: Impact of shallowing on the chloride concentration at Brienenoordbrug. The figure presents the time series of for the reference case (grey lines in the background) and the shallowing states (orange lines). The two horizontal lines correspond to the 150 mg/l and 400 mg/l thresholds for drinking and agricultural water use, respectively.

4.2. Implications for freshwater supply

This section summarize the most important findings concerning the impact of shallowing on the performance of freshwater supply, and the quantitative relation between bed level change and freshwater supply performance.

Impact on freshwater supply

The effects of shallowing on freshwater supply are assessed through the indicator *salinisation days*. Results were obtained for two end-users: drinking water use (normative value at 150 mg/l), and agricultural water use (normative value at 400 mg/l). Focussing on the drinking water use quantified at Boerengat, results show the duration of non-normative salinisation decreases from 24% (bed level +1.4 m) to 94% (bed level +3.9 m), as seen in Table 4.1. Likewise, values at Brienenoordbrug have a similar trend with a decrease varying between 40% and 100%. In the case of freshwater for agricultural use at Boerengat, non-normative salinisation values seem to decrease over 80% for shallowing levels of 2.9m or more. At Brienenoordbrug, a decrease of over 80% is achieved for any shallowing state.

Table 4.1: Impact of shallowing on the performance of freshwater supply for two reference locations in the Nieuwe Maas. The indicator *salinisation days* is computed in a Matlab script as the duration (in days) in which salinity exceeds the legal standard. The total duration of the simulations is 42 days.

Location	Duration in days >150 mg/l					Duration in days >400 mg/l				
	0 m	1.4 m	1.9 m	2.9 m	3.9 m	0 m	1.4 m	1.9 m	2.9 m	3.9 m
Boerengat NAP -2.5 m	28.4	21.5 (24%)	17.7 (38%)	10.3 (64%)	1.7 (94%)	21.9	14.3 (35%)	10.0 (54%)	3.1 (86%)	0.0 (100%)
Brienenoordbrug NAP -2.5 m	18.4	11.1 (40%)	7.7 (58%)	1.3 (93%)	0.0 (100%)	11.6	2.4 (79%)	0.5 (96%)	0.0 (100%)	0.0 (100%)

Quantitative relation: bed level change vs. freshwater supply performance

The freshwater supply performance indicators were related to the bed level change in the Nieuwe Waterweg through mathematical relations (Figure 4.5). These relations are obtained by interpolating data with a polynomial and exponential models. Results are presented for four cases: drinking use at Boerengat, agricultural use at Boerengat, drinking use at Brienenoord, and agricultural use at Brienenoordbrug.

In all cases, the indicator *salinisation days* is maximum for the reference case (i.e. no bed level increase), and it decreases until zero or approximately zero for a bed level increase of 3.9 m. In three out of the four cases, results show a gradual decrease in salinisation while moving towards higher bed levels. For the agricultural end-user at Brienenoordbrug, results indicate a steep decrease in salinisation days for the first 1 m of bed level increase, and then a soft decrease for higher values.

Besides, an uncertainty analysis was conducted for the fitting models. It includes the estimation of the goodness of fit, the calculation of the uncertainty in the fitted functions, the width of the 95% confidence intervals, and a visualisation of the confidence bounds. Detailed information and visualisations are presented in Appendix D. Results show that the goodness of fit of the interpolation, estimated by the R-square parameter, is always above 0.97. Furthermore, when looking at the confidence bounds, it can be seen that the bound width is below three days at Boerengat (both for drinking and agricultural use), and for agricultural use at Brienenoordbrug. Conversely, the bound width for drinking use at Brienenoordbrug is significantly larger (see Table 4.2).

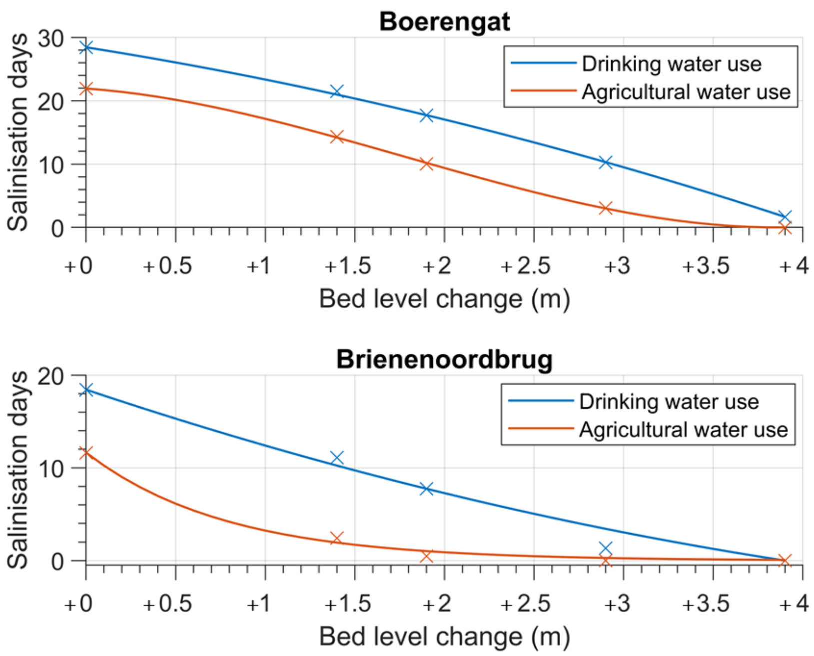

Figure 4.5: Relation between *bed level change* and *Salinisation days* for the two study locations, Boerengat and Brienenoordbrug. Values of the indicator were calculated for two freshwater standards, 150 mg/l for drinking use (red dots) and 400 mg/l for agricultural use (black dots). For each case, data was fitted to polynomial or exponential functions (blue and orange lines). More details about the mathematical functions used to fit data is presented in Appendix D.

Table 4.2: Uncertainty of the fitting mathematical functions used to interpolate *salinisation days* data. The table show approximate values obtained from the information in Appendix D.

	Boerengat		Brienenoordbrug	
	Drinking water	Agricultural use	Drinking use	Agricultural use
Conf. bounds width	1 day	2-3 days	4-6 days	2 days

4.3. Implications for port logistics

To assess the effect of shallowing on port efficiency, the OpenTNSim model was used to assess the impact for the reference state and six levels of shallowing. The following items summarise preliminary results obtained from the comparison tool. First, relevant results from the modelling study are summarise. Secondly, the quantitative relation between bed level change and port efficiency is presented.

Impact on port efficiency

For each of the seven states modelled, statistic parameters such as the average, standard deviation, and error of the indicator *Average Waiting Time* were derived over seven sets of simulation runs.[1] The most important outcome is the mean value of the indicator. It can be seen from the information presented that the *Average Waiting Time* slightly decreases for shallowing levels from +0.0 m to + 1.9 m, after which it starts to increase gradually until + 3.3 m. For a bed level increase over + 3.3 - 3.6 m, waiting times increase steeply (Table 4.3).

An important result to emerge from the information presented is that the standard deviation and error of the *Average Waiting Time* is relatively low until a shallowing level of + 3.3 m. Then, however, it dramatically declines for the last two shallowing states, i.e. + 3.6 m and + 3.9 m (Table 4.3). A closer look at the set of runs shows that the average waiting time varies significantly from one run to the other for both shallowing states mentioned. Moreover, the waiting times can reach up to 30 hs to 70 hs. Information about each set of runs is presented in Section C.2.

[1]Each set of runs consisted of 10 to 15 runs.

Table 4.3: Results from the OpenTNSim model. The mean and standard deviation of the indicator *Averaged Waiting Time* is calculated over the number runs. What stands out in this table is that, for the last two levels of shallowing, the standard deviation is larger than the mean value.

Bed level change (m)	+0 m	+1.4 m	+1.9 m	+2.9 m	+3.3 m	+3.6 m	+3.9 m
Number of runs	15	10	10	10	10	11	15
Average Waiting Time (hs)	0.286	0.194	0.161	0.598	0.920	8.79	13.73
Accuracy (% of WT)	9	8.5	10	11	5	95[1]	80[2]

[1] Some cases with waiting times of up to 42 hs, [2] Some cases with waiting times of up to 71 hs

Terminal and anchorages
Relevant results include the average terminal occupancy, number of vessels served, and average anchorage occupancy (Table 4.4). For the reference case, the Koole terminal occupancy is ∼ 0.38 and the anchorages, with a maximum capacity of 50 vessels, have a negligible occupancy. Both terminal and anchorage occupancy increase gradually between the reference state and the + 3.3 m shallowing state. For higher values of the bed level, av. terminal occupancy jumps from 0.48 to 0.68. The av. anchorage occupation does not increase significantly, but it get close to 1 for a few simulations for shallowing levels over +3.3 m. A similar observation is made for the number of vessels served, which jumps from 480 (+3.3 m) to 713 vessels (+3.6 m). The terminal throughput for the reference state is 12.76 Mm3, and it was kept constant for all simulations. To this end, the inter-arrival time of vessels was changed for each shallowing state.

Arrival process
The resulting varying inter-arrival time of vessels is shown in Table 4.5. This parameter is bounded to the fleet composition and the system intervention. A fleet composition with more classes and bigger vessels is related to lower shallowing states (close to the reference state in Table 4.5). In this case, the terminal throughput is achieved with higher inter-arrival times than higher shallowing levels. Conversely, for higher shallowing levels, the target throughput is achieved with a significantly increased number of vessels served at the terminal (close to +3.90m bed level change in Table 4.5). For the latter case, the fleet comprises six to five vessel classes, smaller in size than the reference case.

Table 4.4: Operations at the terminal and anchorage areas.

Bed level change (m)	+0 m	+1.4 m	+1.9 m	+2.9 m	+3.3 m	+3.6 m	+3.9 m
Throughput (m3 x 10E6)	12.756	12.760	12.731	12.731	12.731	12.702	12.702
Av. terminal occupancy	0.38	0.42	0.46	0.47	0.48	0.68	0.69
Av. # of vessels served	390	431	473	473	480	714	713
Av. anchorage occupancy	6.0E-4	3.0E-4	3.0E-4	1.1E-3	2.0E-3	1.2E-2[1]	1.6E-2[1]

[1] Anchorage congestion (occupancy =1) in some cases.

Table 4.5: Fleet composition and arrival process from the traffic modelling study with OpenTNSim.

Bed level change (m)	+0 m	+1.4 m	+1.9 m	+2.9 m	+3.3 m	+3.6 m	+3.9 m
Fleet composition (# of classes)	8	7	6	6	6	5	5
Design draught (m)	15.0	13.6	12.1	12.1	12.1	11.4	11.4
Av. vessel inter-arrival time (hs)	10.0	9.1	8.4	8.4	8.4	5.6	5.6

Quantitative relation: bed level change vs. port efficiency

The *average waiting time* was related to the *bed level change* in the Nieuwe Waterweg (Figure 4.6) through an exponential interpolation. Compared to the freshwater supply case, two additional shallowing levels were simulated in OpenTNSim (+ 3.3 m and +3.6 m). This choice was made to increase the fit quality in the region where the average waiting time increases steeply. The fitting model gives more weight to the first five values, as these are more reliable than the last two. The resulting function leads to a nearly constant value of the waiting time (0.15 to 0.20 hs) until a bed change of + 2.0 - 2.2 m, after which it starts to increase exponentially.

Besides, an uncertainty analysis of the fitting function was conducted. Here, only a summary of this analysis is presented. For detailed information and visualisations of the uncertainty analysis, the reader is referred to Appendix D. Results show that the goodness of fit is estimated with an R-square of 0.91. The most interesting aspect is the width of the 95% confidence intervals. For the first 3 m of bed level increase, results indicate that the bound width is six times the average of ~ 0.2 hs. For a bed level increase over 3 m, the bound width is 1.5 to 2 times the average (see also Figure 4.6).

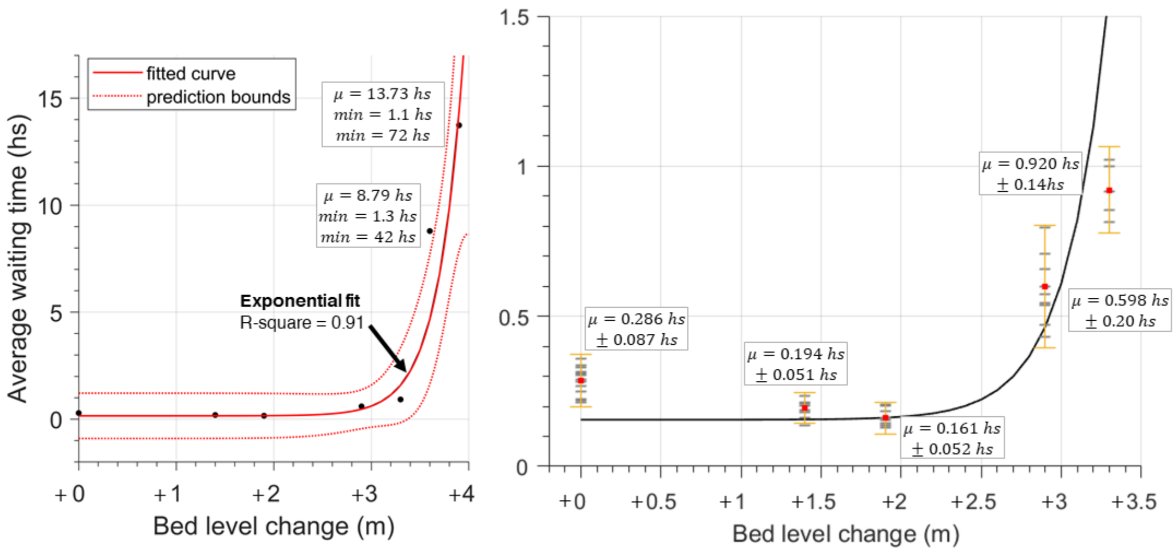

Figure 4.6: Relation between *bed level change* and *Average Waiting Time*. Left: The figure presents seven points, including the reference state and six shallowing states, and the exponential fitting function (red solid line). Also, it includes the confidence bounds for the fitting function (red dashed lines). Right: The plot is an error bar graph of the *Average Waiting Time* calculation with OpenTNSIm. The bars correspond to the 95% confidence interval (bounds in yellow and mean value as a red dot). Each realisation in OpenTNSim is depicted inside each error bar (grey hyphens). Only the reference state and four shallowing states are presented in the right plot (up to + 3.5 m of bed level increase). The remaining two shallowing states have a confidence bound several times larger than the mean value.

4.4. Resulting trade-offs

This section presents the final and most important outcome of the comparison tool. The two individual relationships shown in Figures 4.5 and 4.6 gave place to a quantitative trade-off between the freshwater and port logistic objectives. For this case, four visualisations of trade-offs are possible, two for Boerengat and two for Brienenoordbrug (Figures 4.7 to 4.8). In general, it is observed that trade-off curves behave asymptotically. The tail on the bottom-right represents lower values of the port objective with higher values of the freshwater supply objective. The tail on the upper-left resembles the opposite situation. Results show that, in general, original pairs of data values correspond to the trade-off curve (see red crosses in Figures 4.7 and 4.8).

One aspect to emerge is the systematic deviation of the reference state from the trade-off curve, in which the curve is always 0.13 hs lower than data for the four cases. The systematic error originates in the exponential interpolation to waiting time data. For more clarification, the reader is referred to the average waiting times fitting curve in Figure 4.6.

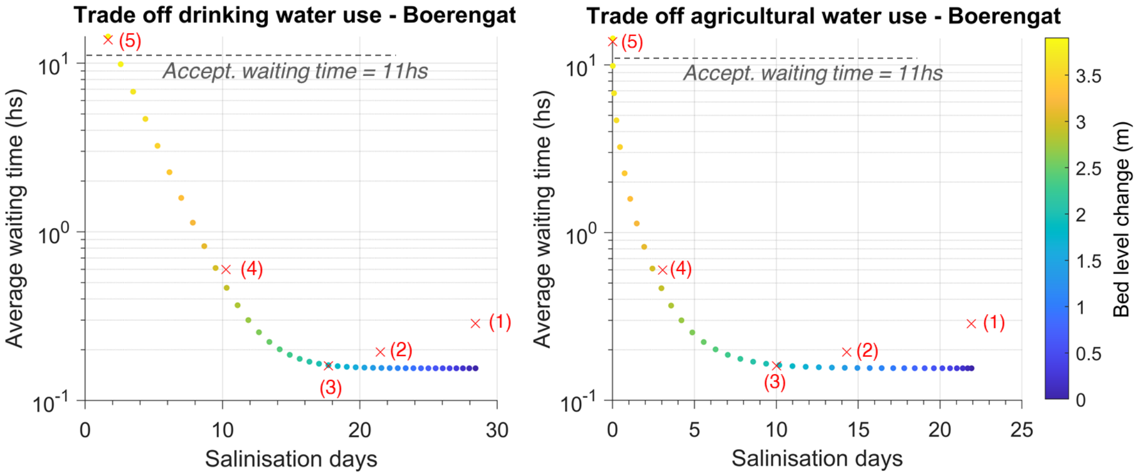

Figure 4.7: Trade-off visualisation for port efficiency against freshwater supply at Boerengat, for drinking water use (left plot) and agricultural water use (right plot). The figure shows the relation between *Average Waiting Time* (on a logarithmic scale) and *Salinisation days* depicted as a curve. Also, the five pairs of data values obtained from the modelling studies are depicted as red crosses. The colour bar on the right shows the increase of bed level measured from the reference case. In addition, the figure presents the desired state for the two end-users. The acceptable waiting time is 11 hs and is represented with an horizontal dashed line. The desired state for the freshwater supply objective is 0 salinisation days. References in the figure: (1) Reference state + 0.0 m; (2) Shallowing + 1.4 m; (3) Shallowing 1.9 m (4) Shallowing 2.9 m; (5) Shallowing 3.9 m.

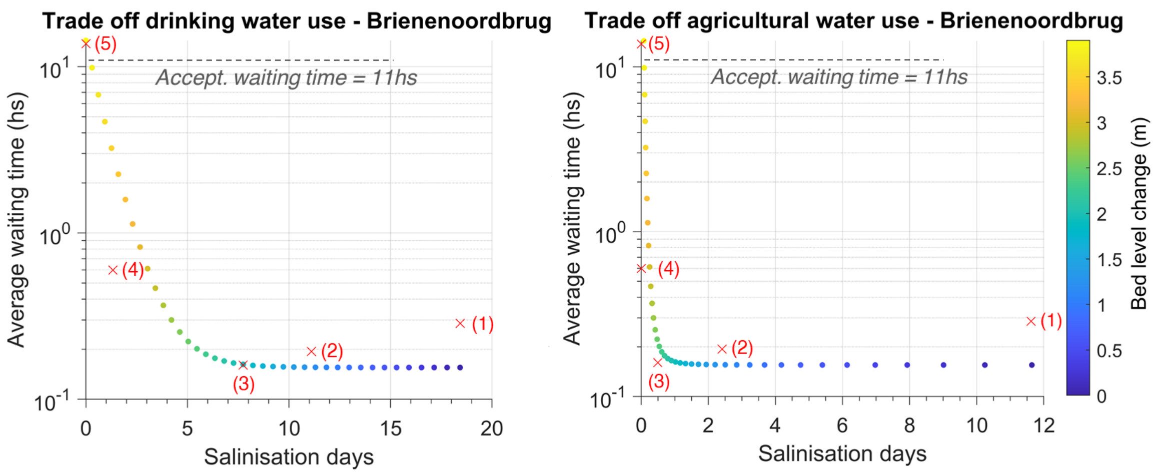

Figure 4.8: Trade-off visualisation for port efficiency against freshwater supply at Brienenoordbrug, for drinking water use (left plot) and agricultural water use (right plot). The information is presented in the same manner of Figure 4.7. References in the figure: (1) Reference + 0.0 m; (2) Shallowing + 1.4 m; (3) Shallowing 1.9 m (4) Shallowing 2.9 m; (5) Shallowing 3.9 m

5

Discussion

This chapter is divided into four parts. First, Section 5.1 discusses general aspects about the resulting comparison tool. Secondly, Section 5.2 focus on the implementation of the tool in the case study and put results in the context of management decisions in the Rhine-Meuse Delta. Thirdly, Section 5.3 discuss the implications of the main assumptions and simplifications in the methodology. Fourthly, Section 5.4 discuss the uncertainty in the results obtained from executing the tool in the case study.

5.1. A systematic comparison tool

This section starts by posing general considerations regarding the comparison tool through four main aspects: significance of the resulting comparison tool, advantages of the methodology, uncertainties in combining two or more stakeholders, and challenges in applying the objectification process.

5.1.1. Significance of the resulting comparison tool

The first important outcome of this study is a tool founded on Building with Nature principles, which can be used to perform combined assessments amongst multiple stakeholders. Furthermore, this study demonstrated that the comparison tool could be embedded in the objectification process through the FoR approach. In doing so, it can be applied systematically according to a simple procedure in which: (a) the system intervention is defined; (b) several parallel assessments are conducted; and (c) the outcomes of the individual assessments are combined.

Above all, this study has shown that conflicts between stakeholders can be measured and visualised quantitatively, even if their objectives are very dissimilar. Decision-makers can use such information to understand the implications of interventions to the system from a multi-stakeholder perspective. Moreover, the most important added value of the comparison tool is the possibility to handle multiple stakeholders and understand their interactions, which is crucial to delivering successful nature-based solutions [Eekelen et al., 2020].

Advantages of the methodology

A particularly interesting aspect of this tool is its capability of handling very dissimilar performance indicators. It means that the trade-off assessment does not necessarily have to be done through a uniform unit (e.g. monetary units). That increase the range of applicability of this study provided that changes in stakeholder performance can be somehow modelled and quantified. In the planning and design phase of a project, the comparison tool can provide meaningful insights in evaluating alternatives for cases where one or more environmental aspects cannot be translated into monetary units.

This study showed that the tool could combine freshwater supply and port performance indicators in the context of salt intrusion-induced problems in urbanised deltas. Since this tool is systematic, it can be used regardless of the targeted stakeholder of the assessment. For instance, water safety could be addressed by quantifying changes in the design water level. Alternatively, nature could be included through quantifying ecological effects via changes in biodiversity (such as the Nature Index tool by Ecoshape [2021], Sijtsma et al. [2009]). Finally, if spatial development aspects are translated into measurable units, they could also be embedded in the combined assessment. However, the comparison tool is not applicable in cases where these changes cannot be modelled and quantified. Despite this limitation, it is seen that the comparison tool can shed light on understanding relations between the crucial stakeholder functions in an urbanised delta.

Uncertainties in combining two or more stakeholders

From the results of this study, it can be ascertained that the comparison tool delivers quantifiable relations for two stakeholders. However, there are still many unanswered questions about the efficiency of the methodology undertaken if more than two stakeholders are combined. One challenge encountered in this study was coupling models with different time and spatial scales. This is the case of the OSR and OpenTNSim models used in this research.

On the one hand, salt transport processes are highly dependent on 3D physical phenomenon [Geyer and MacCready, 2014]. Obtaining salinity variations at water inlet locations required 3-dimensional water and salt transport computations in the entire estuarine domain. Due to time constraints, the simulation time was limited to slightly more than one spring-neap period. On the other hand, the OpenTNSim required 1D hydrodynamics from the OSR-model to calculate tidal windows in the waterways. Thus, the time-consuming resolution of 3-dimensional hydrodynamics was not strictly necessary for the second model. In the end, the OpenTNSim model could efficiently solve meso-scale traffic flows over a simulation time that is six times larger than the modelling study with the OSR. This mismatch in the computational effort by the two models provides some evidence that coupling and solving very distinct physical processes might lead to an inefficient modelling methodology. Despite this inefficiency, the modelling studies in this research could be carried out within the expected time and accuracy. However, it is unclear how complex the modelling methodology could be if more dimensions are added to the problem. To develop a complete picture of how efficient the comparison tool is, additional studies will be needed that address the performance of a third (and even a fourth) stakeholder.

5.1.2. Challenges in applying the objectification process

This study was built on the principles governing the quantitative assessment of nature-based solutions. For that purpose, the Frame of Reference approach by van Koningsveld [2003] and the objective-based assessment by Laboyrie et al. [2018], was used. Even though the proposed comparison tool achieves its ultimate goal of providing objective-based and quantifiable knowledge, there were two main challenges in following the decision recipe in the FoR approach.

First, the *evaluation* of the operational and strategic objectives is not explicitly incorporated in this study. Therefore, a logical question will be if the chosen strategy achieves the aspects that stakeholders consider essential. In this work, technical studies from the Netherlands were used as input to answer this question (see also Subsection 2.6.3). However, if it turns out that the stakeholders do not embrace the formulated objectives, the resulting measurable variables may be misleading Laboyrie et al. [2018]. Then, the entire modelling approach may not provide the correct answers or lead to unnecessary efforts to obtain results. Despite this uncertainty, this study selected a strategy and successfully proved the principles in the FoR procedure.

Secondly, one of the most challenging tasks in the objectification process is designing a measurable quantity related to the operational objective. The proposed procedure guides the user to obtain one indicator related to one stakeholder function for each operational objective. However, since this objective depends on many specific interests related to the same stakeholder, it is not easy to represent it via one indicator. In the case study, this issue was particularly challenging for the objectives of freshwater supply, as illustrated through the example below. In the end, an inevitable mismatch between the operational objective and the indicator was accepted.

Formulation of the operational objective for freshwater supply end-users

According to the operational objective formulated for the freshwater supply function, optimal water quality would be achieved by decreasing the indicator *salinisation days* indicator to zero. In this study, it was assumed there is a constant freshwater demand, and no other external sources of water are available. That implies that water shortages would occur every time salinity levels are above the normative value, which is not necessarily the case. To mention a few important points of discussion:

- Water consumption (demand) might diminish during certain periods. Nevertheless, the problem of salt intrusion is largest during droughts, during which the demand can be expected to increase instead of decrease. Then, the assumption about a continuous water demand seems representative of a worst-case scenario.
- Concerning the previous point, the daily fluctuations of water demand could be at a different time scale than occurrences of non-normative chloride values. Then, periods of demand may occur at different intervals than periods of saltwater pollution of the freshwater system. A more sophisticated analysis could be conducted, including both time scales.
- Water inlets could have sufficient capacity to cope with the demand when short inlet windows within a day are made available. However, the capacity may be limited for certain inlets. Then, neglecting higher supply capacity from the analysis is considered a conservative decision.
- Freshwater systems can count on additional storage or infrastructure such as weirs, waterways and pumping stations that supply fresh water to vulnerable areas. However, the transport of freshwater from other areas is limited, and the necessary infrastructure may not be available in the entire estuary. In addition, using groundwater reserves is a very unsustainable option. So then, neglecting additional water storage from the modelling study is deemed a conservative decision.

The latter four points of discussion raised the possibility of looking at other types of indicators to assess the operation of the freshwater system differently. For instance, by considering the indicator *daily inlet windows duration*, it could be assessed on the changes of inlet window duration to understand better how much freshwater can be extracted from the system within a day. Also, indicators such as *frequency* and *duration* of single exceedance events could be used to assess the effect on the deployment of contingency measures. Looking back at the operational objective, it is seen that providing an optimal water quality for freshwater supply is not exclusively achieved by reducing the indicator *salinisation days*. So, to upgrade the assessment carried out in this study, the formulation of the operational objective should be tailored to specific receptor targets and the freshwater system's complexity. For the sake of comprehensibility in the implementation of the tool, a mismatch between the operational objective and the indicator *salinisation days* was accepted. In the end, this decision led to conservative results about the duration of water shortages. Above all, this work proved that it is possible to follow the FoR procedure in assessing the performance of nature-based solutions for salt intrusion.

5.2. Implementation of the comparison tool in the context of the Rhine-Meuse Delta

During this research, much of the effort was focused on implementing the comparison tool in the Rotterdam Waterways case study. This application was meant to relate impact on freshwater supply and port logistics. This section puts results in a larger context involving the shallowing plan for future scenarios in the Rhine-Meuse Delta. The section is divided into two main parts. First, the resulting trade-offs between freshwater supply and port performance are discussed. Secondly, different ways of using the comparison tool are offered to answer, at least partially, questions concerning the execution of the shallowing plan for freshwater supply, port, nature, and water safety functions. Results concerning freshwater supply and port efficiency are treated in detail, whereas nature and water safety are discussed briefly.

5.2.1. Quantitative trade-offs

The novelty in implementing this comparison tool is the ultimate finding of quantitative relations between stakeholder functions affected by an increase of bed level. Furthermore, the resulting trade-off curve provides quantitative insights to support further the hypothesis of a collision of interests between freshwater supply and port logistics.

In all four cases presented in Section 4.4, the curve presents an asymptotic behaviour. It implies that an improvement in the performance of freshwater supply (decrease in *salinisation days*) always goes to the detriment of the performance of port efficiency (increase in *waiting times*). Also, the trade-off curve informs about ranges of values in which this behaviour is more or less pronounced. Here below, the use of the trade-off curves is shown by means of an example in which drinking water supply from Boerengat and the port network efficiency are related (Figure 5.1).

In Figure 5.1, it can be observed that there is a wide range of bed change in which the freshwater supply performance increases significantly without a significant detriment of the port efficiency (i.e. towards the left of the x-axis in the plot). This range lies around 0 to 2 m of bed level increase, a range of values that could be allowed without significantly affecting port efficiency. This value could even reach up to 3 m, and the waiting time would still be at acceptable levels (less than 1 hs), so that a reduction of 33% in *salinisation days* is achieved. For values over 3 m of bed level increase, the decision-maker will likely face a difficult choice. The improvement in drinking water supply performance at Boerengat put this end-user at odds with port-related stakeholders because a decrease in *salinisation days* implies a significant increase in vessels *average waiting time*. Finally, for a bed level increase of 3.5 - 3.9 m, waiting times are likely to exceed the acceptable level specified in 11 hs. It was assumed that the desired state for the freshwater supply function is achieved when the salinisation days are cut down to zero. For the case of drinking water from Boerengat, the trade-off curve suggest this can not be achieved for the levels of shallowing analysed.

To sum up, the latter example shows how a quantitative comparison can be used to identify ranges where efficient solutions are found, tipping points, and whether a measure complies with the operational objectives of the end-user. Before moving on, a note of caution is due here. Since these curves are intimately related to the assumptions and simplifications made in the modelling studies, the exact values from these graphs cannot be used in policy-making. Instead, conclusions about the general behaviour of the indicators could be used to understand better how trade-offs are created. In essence, the following information can be extracted from the four trade-off curves:

- There seems to be a range of bed level increase of approximately < 2 m in which the efficiency of the port network is not substantially harmed. Instead, the performance of freshwater supply is significantly improved via a reduction of shortages in the order of 30-50%.
- If bed level continues to increase above $\sim$ 2 m, waiting times approaches a tipping point in which values start to rise exponentially. For a small improvement in freshwater supply, the service level of the port is rapidly worsened, leading to an undesired state in port efficiency when approaching the + 3.9 m increase.

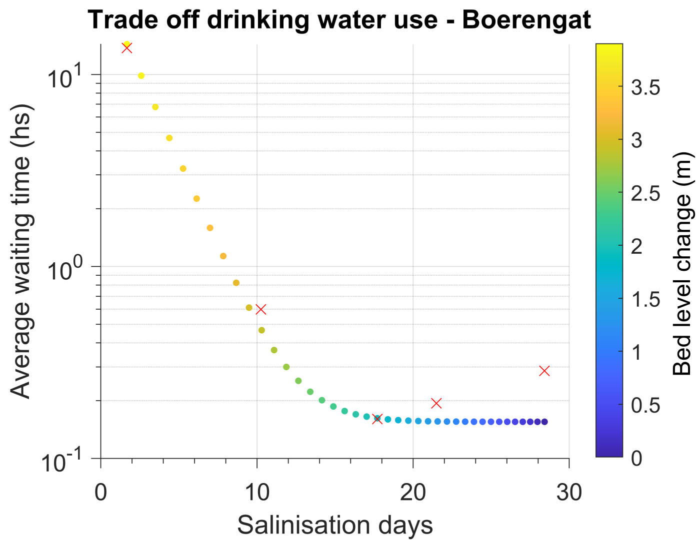

Figure 5.1: Trade-off visualisation for port efficiency against freshwater for drinking use at Boerengat. References in the figure: (1) Reference state + 0.0 m; (2) Shallowing + 1.4 m; (3) Shallowing 1.9 m (4) Shallowing 2.9 m; (5) Shallowing 3.9 m.

5.2.2. Implications of shallowing for freshwater supply

The first hypothesis about implementing the shallowing plan considers this measure a positive contributor to freshwater supply. According to the theory, there are arguments to support the statement that salt intrusion could retreat if the water depth is reduced, leading to a beneficial impact on freshwater supply (see Section 2.6).

In principle, the latter is confirmed by results. Chloride concentrations seem to decrease significantly for the two locations in the Nieuwe Maas. Likewise, the maximum salt intrusion length seems to retreat in the order of a few kilometres for shallowing states (see also Figure 4.2).

Consequently, freshwater supply at Boerengat and Brienenoordbrug could be benefited due to the decrease in the degree and duration of salinisation. The latter was demonstrated for drinking and agricultural end-users. In these cases, the indicator *salinisation days* decreases for an increasing bed level, which translates as an improvement in the freshwater supply performance (Figure 4.5). For all cases, results indicate that the performance of freshwater supply is the poorest for the reference state (i.e. without shallowing). Its best performance seems to be achieved for bed level changes over 3 m, when water shortages are reduced by more than 70%. Also, the desired state (*salinisation days*$= 0$) is usually achieved for a bed level increase > 3.5 m for Boerengat and > 3 m for Brienenoordbrug.

Analysis of water inlets relocation

An expected finding from Figure 4.5 is that the performance of drinking water supply is more susceptible to shortages than the agricultural. In other words, the shortage duration for drinking water is always longer than the shortage of agricultural water. Also, the indicator *salinisation days* is quite sensitive to the normative chloride content, equal to 150 mg/l for drinking use and 400 mg/l for agricultural use. The lower this threshold is, the longer the duration in which salinity exceeds it.

It is interesting to observe that results presented in Figure 4.5 can be used to assess the change in performance when moving from one location to the other. This information could support decision-makers to evaluate possible relocations of water inlets. For example, results indicate that the performance would improve significantly if the Boerengat water inlet were relocated to Brienenoordbrug, just 3 km upriver. For the reference state, water shortages would decrease by about 35% for drinking use and 45% for agricultural use. In addition, the proposed relocation would improve the performance when shallowing is implemented, although the upgrade is not significant for bed level changes over 3 m. As seen, the visualisation of these plots enables quick assessments for decision making regarding potential measures such as shallowing, water inlet relocation, or a combination of both.

5.2.3. Implications of shallowing for port performance

A second theoretical hypothesis considered that shallowing could affect the port network performance negatively (see Section 2.7). This study related the increase of the bed level change and waiting times of vessels, which enables an analysis of the effects in terms of port efficiency. The resulting relation is discussed in two parts:

1. **Shallowing below 2 m**: An unanticipated finding was that the increase of the bed level in the waterway leads to a slight decrease in waiting times from 0.3 hs (reference) to 0.16 hs (+1.9 m). Also, these values are far below the acceptable limit of 11 hs. The slight decrease can be explained by comparing the required water depth of vessels against the available water depth in the waterway. Despite the 1.9 m reduction, the available water depth is considerably larger than most vessels' required. In this range, the vessels affected by accessibility restrictions caused by shallowing are only a minor fraction of the fleet. As seen in Figure 5.3, the probability of arrival of classes LR2 and LR2 (lightered) is 3%, around six to ten times lower than the remaining classes LR1 to small coasters. These two vessels classes are tide-bounded, but the remaining classes are not (for more details, see Table 5.1). As a result, waiting times for most vessels are not influenced by tidal windows. Then, the decrease in waiting times for this range of bed level increase would suggest that port efficiency is improving. However, this conclusion could be misleading for two main reasons.

   First, the traffic modelling study was schematised. By simplifying the port network to one terminal and a seagoing route, a large part of shipping operations in the port was left out of the analysis. Also, the fleet distribution and arrival process might be different in reality. The implications of these choices are further discussed in Section 5.3

   Secondly, in the modelling study, it was assumed that the shipping agent would change its fleet, replacing the biggest vessels with an equivalent amount of smaller vessels so that the objective for the throughput capacity could be met. However, this is unlikely since the agent can choose to send vessels to competing ports with a better service level (e.g. Port of Antwerp). In that case, waiting times may drop due to a decrease in the number of arrivals. It could also decrease due to better accessibility conditions for the smaller draught of vessels. However, this drop in waiting time does not imply an improvement in port performance because, in turn, terminal capacity would be severely affected. After all, the largest vessels would not be served anymore.

   For one reason or the other, the slight decrease of waiting time for shallowing levels below 2 m does not necessarily mean an improvement in the port performance. Still, results are helpful to conclude that port waiting times are not expected to increase to an undesired value within this range of bed level increase.

2. **Shallowing between 2 m to 3.9 m**: Results indicate a relatively low negative effect on port efficiency for a bed level increase between 2 and 3 m and a significant negative effect for levels higher than 3 m. This behaviour is seen in the exponential increase in average waiting times. In this range, it seems the risk of port congestion becomes a concern due to the vast number of vessels in the network and the high occupancy of the terminal. There are two possible contributors to the large increase in waiting times.

   First, the increase in waiting times could be originated from the change in fleet composition. Results showed that replacing bigger vessels with an equivalent amount of smaller vessels led to a great increase in terminal operations, which can be observed by a significant jump in the number of vessels served. The occupancy in the waterways and the berths are bounded to the waiting times [Groenveld, 2001, van Koningsveld et al., 2021]. The latter is useful to explain why waiting times increase so dramatically when the occupancy at the berths is over 0.65 - 0.70. Moreover, findings indicate that anchorage occupancy reaches its maximum on a few occasions for shallowing levels above 3 m, giving signs of imminent congestion.

   Secondly, vessels are time-limited by tidal windows conditions [Olba et al., 2015]. For the higher levels of shallowing, a more significant part of the fleet is affected by water depth reduction. For instance, in the shallowing level + 3.9 m, the largest tide-bounded vessel class is the Medium Range tankers, which represents 15% of the vessel generated during the simulation (see also Figure 5.3 and Table 5.1). Therefore, many vessels are affected by vertical tidal windows, which likely influences the resulting average waiting time at the end of the simulation. In addition, results showed an increase in the average velocity magnitude due to shallowing. Hence, the duration above the critical cross-current could reduce the available horizontal tidal window, increasing the vessels waiting times.

In conclusion, there are two contributors (increased traffic or more burdensome tidal window restrictions) to the increase of waiting times. Results cannot ascertain which one is more relevant. However, the main takeaway message from this discussion is that sufficient evidence was provided to conclude that the shallowing levels in the range 2 m - 3.9 m can be associated with an exponential increase in the *average waiting time*. Furthermore, the growth in this indicator suggests that the port's service level can reach an undesired state. Altogether, these findings confirm the hypothesis made in Section 2.7 that the decrease of water depth can result in an inefficient network, harming the competitiveness of the port.

Future scenarios for shipping and port planning

Previously, findings from this research were used to analyse two possible scenarios concerning the interaction between port-related actors:

- The shipping agent decides to adapt its fleet, replacing the largest vessels with an equivalent amount of smaller vessels, so the throughput requirement of the terminal operator is met. However, the service level in the port is worsened due to an exponential increase in waiting times.
- The shipping agent send vessels to competing ports with a better service level. Waiting times at the Port of Rotterdam are expected to decrease at the cost of decreasing the terminal's capacity.[1]

In these two scenarios, the port loses competitiveness. However, it was assumed that the current port layout does not change in both. Then, results from this study could be used to discuss future scenarios considering a different port spatial development. In such scenarios, long term predictions in the vision of the Port of Rotterdam Authority should be considered. Good flows may stabilise and even increase under scenarios dominated by fossil energy, whereas they may stabilise and even decrease under faster energy transition scenarios [Port of Rotterdam Authority, 2019]. In the discussion to follow, it is assumed that the throughput does not change in the future.

In a fossil-driven scenario, the Botlek area and Petroleum harbours maintain a strong position as an industrial oil cluster, and tanker sizes are expected to keep the same size [van Dorsser et al., 2018]. However, terminal throughput cannot be sustained since the largest vessels (e.g. Long Range 2 tankers) cannot access those port areas. Then, a possible way to compensate for the loss in port capacity is to relocate part of the port areas to offshore and deeper locations where LR2 tankers can access.

Conversely, a fast energy transition would bring developments in bio-fuel, biochemical, and hydrogen cargo, which could be handled by smaller tankers [van Dorsser et al., 2018]. For instance, cargo could be transported to the Botlek and Petroleum harbours with Long Range 1 tankers for a shallowing level of 3.9 m (see also Table 5.1). However, the network would be loaded with many vessels to sustain the same terminal throughput. As explained at the beginning, this situation leads to undesired waiting times and even the failure of the network. Then, to keep a suitable service level, the port could be forced to decrease operations in the land seaports. Then, the resulting decrease in port capacity can be compensated by relocating terminals offshore. Thus, nautical infrastructure with a sufficient capacity should be designed to cope with the increased number of vessels.

To conclude, the shallowing measure does not look promising for certain port-related stakeholders in either of the two future scenarios. In both, the port could be forced to relocate terminals to offshore locations where deeper and more capacious nautical infrastructure can be designed. However, this is not ideal for the port authority, as the new infrastructure could require large investment costs. At least in

[1] This scenario was not included in the modelling study, but it was discussed in the previous Subsection.

terms of capacity and efficiency, and assuming a constant throughput through time, such an investment does not seem to improve the port's status. Thus, the investment to relocate port terminals offshore might not be driven by benefits for terminal operators or shipping agents, which greatly influences decision-making by the port authority.

However, considering port sustainability aspects could provide arguments in a different direction. For instance, the shallowing solution could lead to a significant decrease in dredging volumes, which can be translated as a benefit for the Port of Rotterdam Authority[2]. Hence, it is crucial to keep in mind that a comprehensive assessment should include more aspects about port performance besides capacity and efficiency.

5.2.4. Implementation of the comparison tool for nature

This study focuses on assessing the effects of shallowing from the perspective of freshwater supply and port-related actors. However, it is worth looking at the broad perspective of other stakeholders in the estuary system. In particular, it could be considered how the shallowing solution can benefit natural habitats. This way, environment-related actors could be included in a combined assessment that brings together and compares their interests against others. In the context of delta management in the RMD, a plea for investigation was proposed to explore the effects of shallowing as a potential nature-based solution to restore estuary ecosystems [Meyer, 2020]. There are at least three points of discussion in which this study could contribute:

- **Mudflats and salt marshes development:** A shallowed river could enable the creation of mild and soft transitions at the banks. This new configuration of the river cross-section can enable the development of mudflats and salt marshes [Middelkoop et al., 2003], which currently is not possible due to the steep banks of the Nieuwe Waterweg [Paalvast, 2014]. This research took a step forward by including the 1-dimensional bed level change. Then, including the combined effect of bed level and river width changes on hydrodynamics and salt transport might contribute to assessing ecological effects.

  Also, the development of biodiversity in mudflats and salt marshes could be quantified and then included in the comparison tool (e.g. through the Nature Index tool by Ecoshape [2021], Sijtsma et al. [2009]). Then, biodiversity indicators can be traded-off against the performance of other stakeholders.

- **Abiotic conditions enhancing biodiversity:** Changes in the behaviour of the tide is crucial for the development of vegetation in intertidal areas [Paalvast, 2014]. Also, salt transport dynamics (salt concentration, variability, and gradients) control how salt-sensitive species can grow [Paalvast, 1988]. The latter include, for instance, migratory fish species. As one potential application of this study for future research, the OSR numerical model can be used to obtain quantifiable knowledge about the longitudinal salinity variation. For example, this information can be used to identify how shallowing affects zones of strongly brackish, weakly brackish, or freshwater (see Figure 5.1).

- **Protection of Natura 2000 areas:** Legal standards stipulated in Natura 2000 or the Water Framework Directive legislation are usually expressed as a limit in the yearly-averaged chloride content. Unfortunately, results from this research cannot be used to assess the impact of shallowing for yearly-averaged magnitudes because simulations were carried out for 42 days. Nevertheless, the OSR model (coarse grid) can obtain results over 1-2 years (personal communication from Lamber Hulsen, Port of Rotterdam Authority). For longer time scales, other types of models could be used, such as the SOBEK-RE NDB 110 as part of the Delta Model [Prinsen et al., 2014], but the methodology applied in this study would be the same.

[2]In the Port of Rotterdam, around 14.5 million m3 are dredged per year.

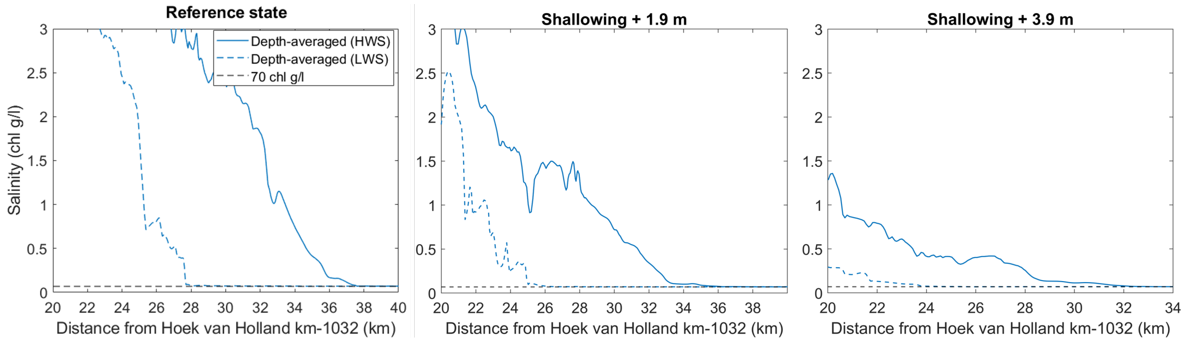

Figure 5.2: Longitudinal depth-averaged salinity variation during slack waters, as computed with the OSR Model. Results were obtained for a of neap tide and mild wind conditions. The figure shows only the last 10 km of the salt-fresh water mixing area on the landward edge. It presents the salinity for High Water Slack (HWS) on the 24-06 at 16 hs (solid blue line) and Low Water Slack (LWS) on the same day at 10 hs (blue dashed line). These two moments correspond to the maximum and minimum salt intrusion length during the simulated day. The background river chloride concentration is 0.07 g/l (grey dashed line). From this figure, it is possible to identify parts of the estuary with continuous freshwater presence (right of the solid line), parts with continuous brackish water (left of the dashed line), and parts with six-hourly alternation between fresh and brackish levels.

5.2.5. Implementation of the comparison tool for water safety

This research does not provide answers for water safety-related actors in the Rhine-Meuse Delta (e.g. Water Boards, Rijkswaterstaat) because the scenarios considered in the modelling study were not based on extreme flood events. Notwithstanding this limitation, the comparison tool can be used to quantify the implications of shallowing for water safety interests. Then, they can be related to other functional requirements in the estuary. The latter is illustrated through two examples concerning the implications of the shallowing plan proposed by Meyer [2020].

For instance, the comparison tool could be used to investigate the relation between shipping operations in the Nieuwe Waterweg and the operation of the Maeslantkering storm barrier for future sea level rise scenarios. Increasing sea level due to climate change is expected to lead to a higher closing frequency of the storm barrier [Haasnoot et al., 2018]. In turn, closing off the estuary prohibits shipping access to seaport terminals located landwards of the barrier. If shallowing leads to a decrease of tidal high waters in the Rotterdam area, the expected future closing frequency could be reduced, creating an opportunity for co-benefits of water safety and shipping operations. Research supporting this statement has been carried out recently [Hensen, 2021]. Conversely, if shallowing results in higher waters and a higher closing frequency of the barrier, the project would create two opponents. Given the relevance of water safety and port-related matters for decision-making in the RMD, it is worth further examining this interaction.

A second example pertains to the implications of a new division of roles between the Nieuwe Maas/Nieuwe Waterweg and Haringvliet systems. One of the most critical aspects of the plan by Meyer [2020] is the discharge diversion from the Nieuwe Maas/Nieuwe Waterweg to the Haringvliet, in such a way that the latter takes the dominant role with around three times the Nieuwe Waterweg discharge. The flow diversion could compensate for the loss of hydraulic conveyance of the shallowed Nieuwe Waterweg, which would prevent an increase of flood water levels in the Rotterdam area. However, due to the decrease in water depth, the Nieuwe Waterweg would be navigable only for inland vessels and small coasters, decreasing the capacity of landward seaports. Then, it becomes clear that knowledge is lacking concerning the potential trade-off between water safety and port-related actors. So is this situation when the comparison tool could come into play to shed light on this relation.

5.3. Assumptions and simplifications in the methodology

This section discusses the implications of the assumptions made to simplify the freshwater supply and port systems.

5.3.1. Assumptions in the freshwater supply system

Results from the impact assessment suggest that shallowing benefits freshwater supply significantly. However, it should be considered that these findings hold for the conditions used in the modelling study and a simplified freshwater supply system. These two aspects are discussed below:

Simplification of climate scenarios in the modelling study

It becomes clear that the study covered only a part of all the environmental scenarios in the RMD. Other environmental conditions with potential impact on freshwater shortage include storm events and post-storm salinisation effects were not considered (Types 1 and 2 according to the classification presented in Section A.3). Likewise, the modelling study did not consider future projections of sea level rise, storms, wind, and long drought events. If these climate conditions were included over different time and spatial scales, the performance of freshwater supply might result differently.

This research included additional simulations with the NSC-OSR model to contribute to a more comprehensive discussion. Detailed information is presented in Section B.1.4. These simulations were conducted for low storms and low river discharge between 01-01-2017 and 07-03-2017. Under these conditions, Boerengat and Brienenoordbrug are affected by short salinity peaks in the time scale of the storm (< 2 days). In general, it can be observed that the building-up and decay of the salinity peak match the evolution of wind set-up event (see also Figure B.26). In the model, these conditions occur for northerly wind speeds increasing over 10 m/s (see also Figure B.25). These results suggest that salinity is quite sensible to the wind set-up originated at the North Sea, even for values in the order of 0.5 - 1 m. In addition, results suggest that despite a decrease in the magnitude of the salinity peaks, shallowing has a negligible effect in reducing chloride content below the normative standard. In the event of a storm surge affecting the Rotterdam Waterways, the relative contributions of the salt intrusion mechanisms change [Kranenburg and van der Kaaij, 2019]. This would detract importance to estuarine circulation, which is the main mechanism influenced by shallowing (Section 2.6). Then, salinity peaks are likely to be produced by a net flux mechanism driving salt in the landward direction, on which shallowing is expected to have a limited effect. This change of roles could help explain why shallowing does not seem effective in mitigating freshwater shortages during simultaneous storms surges and low river discharge events.

Although not all the possible salinisation events in the RMD were included in the simulations, the modelling study deals with the most common one, which occurs during low river discharge and normal tide conditions [de Vries, 2014]. These conditions are representative of a summer water shortage, a recurrent problem in this delta since the water resource is scarce [ter Maat, 2015]. The analysis of these environmental conditions is much more relevant than for events of low river discharge with extreme storm surges, which typically occur autumn or winter [de Vries, 2014] when there is plenty of freshwater supply from RMD rivers to guarantee freshwater supply [ter Maat, 2015]. However, it was seen that salinity peaks do not necessarily occur during extreme storms but also for less severe events. In particular, wind set-up events of 0.5 - 1 m have an exceedance frequency in the order of a hundred times per year [Dillingh, 2013]. Thus, salinisation events associated with these conditions are likely to occur in the summer months, threatening water supply. To conclude, an analysis including low river discharge and small wind set-up events could be the next step in providing more comprehensive answers about the effects of shallowing on freshwater supply.

Simplification of the freshwater system

In addition, it should be noticed that the impact assessment for freshwater supply is based on two locations on the Nieuwe Maas. However, when considering the souther part in the estuary, the performance of water inlets may not be considerably improved by shallowing. Important water inlets are located in the southern branches Oude Maas, Spui, and Haringvliet (see also Appendix A). Here, critical salinisation events can be related to storm events with low river discharge. In a phenomenon known as 'post-supply', after-storm high salt concentrations can be flushed out only through the northern branches, leading to a salinisation event that can last for weeks until it is wholly mitigated [de Vries, 2014]. Since shallowing seems ineffective against storm events, freshwater supply in southern inlets may not be benefited from this measure. The assessment of this situation could be done by finding a new relation between bed level increase and *salinisation days* for a southern location.

Shallowing method implemented in the model

In this research, shallowing was implemented as a uniform bed level in which all large scale fluctuations in the reference bed were flattened out. This way, the effect of changing the vertical position of the bed on salt transport could be isolated. However, natural sedimentation processes will hardly deliver such an ideal bed configuration. Complex hydrodynamics and morphodynamic processes in the flow are likely to shape the bed irregularly. First, large scale changes in the bed level (and the water depth) can influence estuarine circulation through changes in the density-driven landward-directed flow [MacCready and Geyer, 2010] and the turbulence energy originated by bottom friction [Savenije, 2012]. Changes in the effective bottom friction can influence the tidal dispersion and netflow mechanisms driving salt intrusion, as explained in Section 2.6.1. Secondly, changes in bed topography on a small scale (locally) influence vertical mixing and thus salt transport [Pietrzak et al., 1990]. Then, it becomes clear that adding irregularities to the bed would incur in additional time-and-spatial scales of the salt transport processes. Consequently, more accurate models than the one used in this research might be required.

To sum up, this study narrowed the investigation to the effects of a uniform and straightforward type of intervention on the system, which might not be entirely realistic. In doing so, the effect of local or large bed irregularities was put aside and a time-efficient modelling tool could be selected. Also, for the sake of comprehensibility, the research methodology could be tailored to a study intending to prove its principles instead of providing definite answers. Finally, the latter was accomplished by proving the principle of a systematic retreat of salt intrusion while increasing the bed level.

5.3.2. Assumptions in the port system and traffic network

The results of the waiting times are somewhat limited by the choices made to simplify some functional aspects of the traffic network and the vessels nautical behaviour. These choices can have implications in final results, as explained below:

Simplification of shipping operations in the network

In the model, only shipping operations to-and-from the Koole terminal were considered. Hence, the influence of shipping in adjacent parts of the model port network was left out of the analysis. To put it into perspective, the Port of Rotterdam handles around 28,000 seagoing vessels per year in all its terminals [Port of Rotterdam Authority, 2020]. These vessels use the same access channel, and a part of them occupies the Nieuwe Waterweg. The simulations in this study used around 1490 seagoing vessels per year in one terminal. Then, it can be seen that the simulations did not consider part of shipping operations. Three issues emerging from this choice relate to:

- The waterway occupancy is influenced by the traffic to and/or from all seaports landwards of the Botlek. The same holds for shipping using the 3rd Petroleumhaven fairways and turning basins. In reality, vessels requesting permission to sail to the Koole terminal have to wait until these waterways and basins manoeuvring areas are available, which likely leads to longer waiting times than calculated by the model.

- The access channel near the river mouth is also affected by shipping operations in Maasvlakte 1 and 2 and Europoort. Therefore, higher channel occupancy could lead to higher waiting times than model calculations.

- Anchorage occupancy is influenced by vessels to other destinations rather than the Koole terminal. By considering this additional number of vessels, the maximum capacity of the anchorage areas could be reached more quickly, with a higher risk of port congestion, compared to the simulations.

Simplification of inland waterways traffic

Inland navigation was not considered in the model. The choice is based on the expectation that shallowing does not affect terminal capacity since the required water depth of inland barges is not challenged. Results show that the available water depth is more than sufficient for the required depth of inland vessels. Hence, if these vessels were included in the model, vertical tidal windows would probably have a minor effect on waiting times and the terminal throughput.

However, vessel waiting times could be affected due to the increase in traffic intensity in the Nieuwe Waterweg and the 3rd Petroleumhaven fairways. In other words, if inland navigation were considered, there could be a significant increase in the occupancy of the nautical infrastructure, likely affecting the efficiency of the network. As a result, waiting times of seagoing vessels could increase, affecting terminal capacity.

Simplification of the fleet composition

Since insufficient information could be found about vessel sizes in the Port of Rotterdam, eight different vessel classes were compiled in a discrete distribution that covered sizes of typical liquid bulk vessels calling at the Port of Rotterdam. A list with only eight vessels might not be the best representation of the fleet composition. The Koole terminal is likely to handle partially-loaded vessels, which suppose that many vessels classes were excluded from the model. Then, waiting times due to tidal windows would be different for these additional vessels, likely affecting the average waiting time of the simulation. Although there is a mismatch with an actual fleet, the model covers at least the range of sizes from the design vessel (LR2) to the smallest vessel calling at the Koole terminal.

Assumptions about the arrival process

In the model, vessels were generated with a uniform distribution. Such a distribution implies that the time between arrivals is the same during the entire simulation. In practice, the arrival process has a different stochastic nature. They usually correspond to a negative exponential distribution when arrivals are completely random or to an Erlang-k distribution when the shipping line has a regular service [Groenveld, 2001, Kuo et al., 2006]. Then, the arrival process used in the simulation may not represent reality. The arrival distribution has consequences for the berth allocation [Olba et al., 2018], which affect the anchorage and terminal occupancy, and ultimately, waiting times.

The assumed size distribution highly influences the arrival of vessels. In this study, a minor fraction corresponds to the largest-draughted LR2 tankers (see Figure 5.3). If the relative proportion of this vessel class is in reality, larger, more vessels would be severely affected by a water depth reduction. Then, based on the same reasoning emerging from the hypothesis presented in Section 2.7, additional vessels waiting for a longer time increases the average waiting time of the simulation. Then, it is crucial that vessel arrivals are validated with actual data (e.g. AIS data) before making any definite assessment about the exact values of the average waiting times obtained in this study.

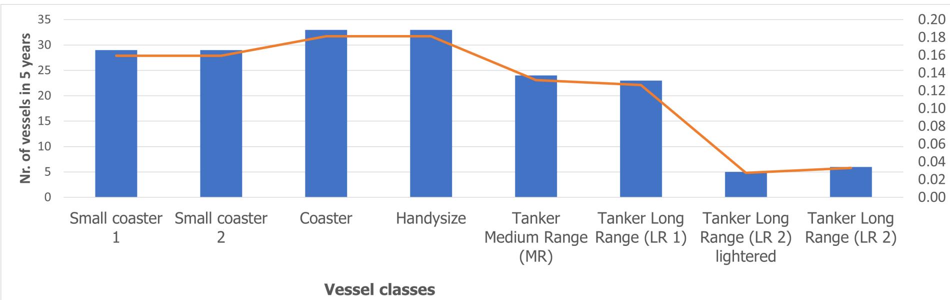

Figure 5.3: Fleet size distribution assumed for the Koole terminal in the 3rd Petroleum Haven.

Schematisation of the bed level

In the modelling study, the bed position in the network is defined by the Maintained Bed Level (MBL) with respect to NAP. According to the PIANC [2014a], bottom-related factors determine the MBL. Among these factors, the safety margin accounts for uncertainties in the dredging works and surveying and tolerances to avoid dredging maintenance works (Section 2.7). In the model, the safety margin was not considered. If it were included, the available water depth of vessels would decrease, likely affecting

Table 5.1: Accessibility conditions of vertical tidal windows based on the Port of Rotterdam policy, as presented in Section 3.3. When vessels do not need a vertical tidal window to access, they are labelled as 'Non-tide bounded (NTB)'. When the accessibility is less than 99%, it is referred as to 'No access (NA)'. When vessels can access during a tidal window during at least 99% of the high waters, they are 'Tide bounded (TB)'.

MBL (NAP m)	-16.4	-15.0	-14.5	-13.5	-13.1	-12.8	-12.5
Bed level change	0 m	1.4 m	1.9 m	2.9 m	3.3 m	3.6 m	3.9 m
Small coaster 1	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Small coaster 2	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Coaster	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Handy Size	NTB	NTB	NTB	NTB	NTB	NTB	NTB
Medium Range	NTB	NTB	NTB	NTB	NTB	NTB	TB
Long Range 1	NTB	NTB	NTB	TB	TB	NA	NA
Long Range 2 (p.l.)[1]	NTB	TB	NA	NA	NA	NA	NA
Long Range 2	TB	NA	NA	NA	NA	NA	NA

[1] Partially loaded vessel.

waiting time calculations.

Berth allocation in the terminal
The model does not distinguish differences in the nautical infrastructure amongst berths in the terminal. Since the queuing routine is 'First Come First Served', this cause vessels to be allocated inefficiently. Small vessels could occupy berths meant for larger vessels, thus blocking access to the largest vessels. In reality, the largest vessels would have priority for the deeper berths.

Vessel speed
Vessel speed is a relevant parameter in determining nautical process [Olba et al., 2018]. The model considers that vessel speed is constant (4.5 m/s). However, in reality, vessels would sail faster in the access channel than in the inner fairways of the port basin. It is rather difficult to predict the effect of this choice for results. However, it can at least be expected that varying vessel speed can affect sailing times [Olba et al., 2018].

Tugs and pilot assistance
The model considers an unlimited number of tugs and pilots. In reality, tugs and pilots are limited. This choice could have led to unexpected higher vessel traffic than if just considering a limited amount of them [Olba et al., 2018].

Simulation time
It is common to find in research that statistics are derived over a yearly basis [Piccoli, 2014]. However, in this study, these were obtained for a half-year time. Due to the randomness of the arrival process, increasing the simulation time could significantly improve the reliability of statistics derived from the model.

5.4. Uncertainty in the results

This last section deals with the uncertainties concerning the two modelling studies used in the impact assessment of shallowing of the Rotterdam Waterways.

5.4.1. Uncertainty in the relation between shallowing and freshwater supply

It is important to bear in mind the possible uncertainties in the performance curves presented in Figure 4.5. These curves mainly rely on: (1) the NSC-OSR model used to generate data about salinisation days, and (2) the mathematical function used to fit data. These two sources of uncertainty are discussed below:

1. **Uncertainty of the data**
   The error related to the NSC-OSR model was not calculated. Instead, this research counted on

the high reliability of the OSR model in salt transport predictions, which was demonstrated in many practical applications in the Netherlands [Huismans and Plieger, 2019, Hydrologic, 2015, Kranenburg, 2015]. Nevertheless, it should be noticed that the NSC-OSR model is available in two grid resolutions: fine grid and coarse grid. Practical applications in the Netherlands were conducted with the fine grid, whilst no salt transport studies with the coarse grid were founded. This model is around three times more refined than the NSC-coarse, but it requires at least ten times more simulation time (see also Section B.0.1). Due to time-efficiency considerations, this research was conducted with the coarse grid model. With this grid, it is not clear if the computation of salt transport is entirely accurate in local irregularities such as harbour basins or bifurcations. As a preventive measure, the study locations of Brienenoordbrug and Boerengat were chosen because of the relatively regular geometry of the surrounding river section. Since this study is a proof-of-concept, it is considered that the modelling methodology is sufficiently accurate to find indicators representing the environmental effects of bathymetry changes.

2. **Uncertainty in data fitting**
   Secondly, the relation between *bed level change* and *salinisation days* was modelled with polynomial and exponential interpolations (see also Appendix D). Results show a narrow uncertainty interval of the fitting function for drinking use at Boerengat and a relatively narrow interval for agricultural use at Boerengat and agricultural use at Brienenoordbrug (2-3 salinisation days). However, for drinking use at Brienenoordbrug, the fitting curve have a significant inaccuracy (4-6 salinisation days). These results indicate that more data should be used when fitting before making any definite statements about using these relations. This task would involve generating more data with the OSR-NSC model, but it was not performed due to time constraints.

Despite the potential uncertainties found, model results are still reliable to predict that the increase of bed level has a retreating effect on the salt tongue for the boundary conditions considered. In fact, the OSR-model proved to be a versatile tool. Since salinity outcomes were obtained for the water suction depth of the water inlet, the computation of *salinisation days* is a good prediction of how the operation of the inlet would be affected by the shallowing solution. Also, this study showed sufficient evidence to associate shallowing with benefits to the performance of freshwater supply during periods of low river discharge and mild wind conditions. Moreover, the uncertainty found (6 days at the most) does not change what is stated before.

5.4.2. Uncertainty in the relation between shallowing and port efficiency

The quantitative relation between *bed level change* and *average waiting time* must be interpreted with caution. Two sources of uncertainty are identified to impact final results. The first one is related to data generation with the OpenTNSim model, and the second concerns data fitting. These two are discussed below:

1. **Uncertainty of the data**
   A certain number of repetitions is required to obtain reliable estimates of the *average waiting time*. As the chosen criteria for the model accuracy, the number of runs corresponded to an error of 10-11% of the average waiting time. As seen from the information presented in Figure 4.6, this criteria was met for the first five data points (*bed level change* of +0.0 m, +1.4 m, +1.9 m, +2.9 m, and +3.3 m). However, what stands out is the rapid decrease in accuracy for the last two data points (*bed level change* of +3.4 m and +3.9 m). In this case, the accuracy is so low that a reliable mean value of the *average waiting time* cannot be drawn from model results. The low accuracy of the *average waiting time* estimator might be related to the random character of the arrival process. During the modelling study, it was observed that the number of vessels served kept a relatively steady behaviour for the first five states (+0.0 m to +3.3 m). However, it differs quite substantially from one run to the other for the higher two levels of shallowing (+3.6 m and +3.9 m)[3]. As a result, the port system behaves quite differently from one run to the other, resulting in high variability in the *average waiting time* from one simulation to the other. To obtain better estimates and narrow the confidence intervals, perhaps a higher number of runs would be required [Groenveld, 2001]. However, the number of runs was not increased further due to time

[3]These results can be verified in Section C.2

constraints. Despite this limitation, findings still provide evidence that waiting times for the +3.6 m and +3.9 m levels are far above the values for the lower shallowing levels.

2. **Uncertainty in data fitting**
   The relation between *bed level change* and *average waiting time* was modelled with an exponential behaviour with positive growth. However, results must be interpreted with caution due to the uncertainty in the fitting. The lower and upper bounds are, at some points, 2 to 3 times the mean value of the indicator *average waiting time* (see also Figure D.5). These results suggest that more data should be used before saying anything definite about the exact values in the fit.

   Besides, it is observed that data has a slightly decreasing trend until a *bed level change* of + 1.9 m followed by a slight increase between + 1.9 m and + 3.4 m before it starts to rise steeply. However, the mathematical function models data with a nearly constant value, overlooking this slight decrease. Therefore, a possible way to improve the estimation could be by interpolating the first five data points (until + 3.4 m) with one mathematical function and then interpolating the other two points with an exponential function. Alternatively, a spline interpolation could be used.

To sum up, the accuracy of the relationship could be improved by increasing the number of runs in each simulation set (i.e. each state), generating more data, and upgrading the fitting model. However, despite the uncertainties found, this study can still be sure about the general behaviour of the indicator *average waiting time* for a bed level increase between +0.0 and +3.9 m. This behaviour can be explained by a mild-to-null decrease followed by an exponential growth for an increasing bed level.

6 Conclusions and recommendations

The overarching goal of the current study was to provide a systematic tool to compare implications amongst multiple stakeholders quantitatively. The 'comparison tool' was required to capture and trade-off the objectives of end-users formulated according to the Frame of Reference (FoR) approach by van Koningsveld [2003]. In particular, the present research aimed to examine the relation between freshwater supply against port logistics objectives via the underlying issue of salt intrusion in urbanised deltas. For that purpose, a case study involving the shallowing of the Rotterdam Waterways was set up to confront these two objectives. The procedure required the use of two modelling studies, the OSR-NSC model for water and salt transport and the OpenTNSim model for port traffic flows. The resulting comparison tool and the outcomes from its implementation in the case study made it possible to answer the research question posed in Chapter 1:

How can quantitative trade-offs be systematically obtained amongst multiple stakeholder objectives affected by nature-based solutions, and how do these trade-offs apply to solutions that mitigate salt intrusion?

In this section, each sub-question is addressed individually.

SQ1. What existing method can be used to systematically obtain quantitative trade-offs amongst multiple stakeholder objectives affected by nature-based solutions?

A literature review was conducted to identify methods to evaluate trade-offs amongst multiple stakeholders affected by an infrastructure solution. The following types of methods were gathered:

1. Non-monetary based, qualitative to semi-qualitative methods: Multi-Criteria Analysis (MCA), Multi-criteria decision analysis (MCDA), Modified URE Method. These methods can be used to build trade-offs from qualitative scoring.

2. Monetary-based, quantitative methods: Cost-Benefit Analysis (CBA), Societal Cost-Benefit Analysis (SCBA), and cost-effectiveness analysis (CEA). These methods can be used to trade-off quantities expressed in terms of money.

3. Multi-Objective Decision Making Problems (MODM) and Multi-objective Optimisation (MO) methods, which can be used to obtain quantitative trade-offs in any type of unit.

A method applicable to this research should be able to capture the objectives of several end-users formulated according to the Frame of Reference (FoR) approach by van Koningsveld [2003]. First, it was considered that outcomes from the FoR approach are expressed as quantifiable indicators. Thus, type 1 methods were left out because of their qualitative character. Secondly, the method is supposed to capture and compare very dissimilar indicators, i.e. expressed in different units. Consequently, type

2 methods are put aside since they require expressing all quantities in a uniform monetary unit. Then, from this literature analysis, only type 3 methods can obtain quantifiable knowledge whilst ensuring that dissimilar indicators are traded-off. However, these methods require high computational efforts to acquire data. They also need specific computational resources, such as complex algorithms and artificial intelligence, which this research did not have. Therefore, due to time constraints and limitations in computational resources, this study did not select type 3 methods. Instead, it took its basic concepts about multi-objective trade-offs, which were later used to develop a new comparison tool.

Through this first part of this research, it became clear that finding relations between objectives can be a concern in assessing impact in infrastructure projects. The latter implies that this work can contribute to the assessment of nature-based solutions through a new tool that can combine outcomes from the FoR approach.

SQ2: What are the founding principles, including the ones in the Frame of Reference (FoR) approach, to develop a tool to quantitatively compare the objectives of multiple stakeholders affected by nature-based solutions?

Initially, this work found that the Frame of Reference approach by van Koningsveld [2003], followed by its adaptation to the objective-based assessment by Laboyrie et al. [2018], provides a decision recipe through six basic steps, which this study referred to as the six principles below:

1. Reflect on the values and interests related to the natural system and the socio-economic context to define the strategic objective.
2. Reflect on the interaction between the natural system and the socio-economic context to define operational objectives.
3. Design measurable quantities or indicators based on the operational objectives in relation to end-users. Also, define the appropriate tools to quantify the indicators (Quantitative State Concept).
4. Specify how to benchmark the performance of the design by comparing the current state against the desired state based on the Quantitative State Concept previously defined.
5. Specify the way and degree in which the system is manipulated to bring it to the desired state.
6. Evaluate the effectiveness of the decisions made by reflecting on the operational and strategic objectives.

This way, a Building with Nature (BwN) solution and its expected effect can be rationalised. Then, measurable quantities can be quantified to assess how the BwN affects a specific functional requirement.

Afterwards, a seventh principle was identified concerning quantitative trade-offs. According to this principle, a quantitative trade-off between multiple objectives requires identifying:

- **Decision variable** as the variable the decision-maker can control to intervene in the system and bring it to the desired state. It is a quantity related to a specific physical feature of the system (e.g. river bed level, width, etc.).
- **Objective function** as a numerical quantification of the performance indicator, defined according to the 3rd principle of the list above (Quantitative State Concept). The performance indicator is dependent on the decision variable.

Then, a quantitative trade-off is obtained by relating two or more performance indicators by the inherent decision variable.

SQ3: What are the required steps to quantitatively compare implications amongst objectives of multiple stakeholders affected by nature-based solutions?

The literature analysis derived from the previous two research questions supports the answer to this question. This study obtained a systematic procedure for the 'comparison tool' from the seven principles found before. The procedure is briefly described through the following three steps:

1. Specify how the system is intervened based on the conceptual Building with Nature design. Here, the decision variable is chosen.

2. A objective-based assessment via the Frame of Reference approach is applied repeatedly, each time for a different stakeholder objective. In other words, the first six principles are put into practice, from defining the project's strategy to the specification of performance indicators. The most important outcome of this process is the individual assessment of effects for each stakeholder objective, expressing how the decision variable and each performance indicator are quantitatively related.

3. Performance indicators are related to each other to build a quantitative trade-off (use of the seventh principle described before). This step is when the added value of this research comes into play, relating dissimilar performance indicators influenced by the same system intervention.

This work concludes that the 'comparison tool' achieved its goal of enabling a combined assessment of effects. The most important added value of the tool is the possibility to build relations within a framework intending to manage several parallel objectives in a nature-based project. This way, the comparison tool better understands the interactions between different end-users. Ultimately, it contributes to stakeholder engagement actions as one of the enablers of BwN solutions.

This study found that the main advantage of the methodology proposed is the capability to handle very dissimilar indicators. Hence, the range of applicability is quite large, provided that stakeholders' performance changes can be somehow modelled and quantified. Furthermore, it implies that the tool handles interactions between the crucial stakeholders in an urbanised delta affected by salt intrusion. However, this study foresees potential limitations in the methodology's time-efficiency in cases when more than two stakeholders need to be combined in the assessment.

SQ4: What are the tasks to be executed in finding quantitative trade-offs between the freshwater supply and port logistics objectives affected by nature-based shallowing as a solution to mitigate salt intrusion?

The required tasks are derived from the comparison tool's procedure described before. These were executed for the case study involving the nature-based shallowing of the Rotterdam Waterways as follows:

1. Progressing levels of river shallowing were specified. The concept of shallowing is schematised as a uniform bed level that results from flattening out fluctuations in the reference river bed. Besides the reference bed, four levels of shallowing were defined as +1.4 m, +1.9 m, +2.9 m, +3.9 m of *bed level change*.

2. The FoR recipe was followed and implemented separately. First, to assess effects on freshwater supply performance and, secondly, to assess the impact on port efficiency and capacity. The specific tasks concerning these two separate assessments were the following:

    - Freshwater supply performance was quantified through the indicator *salinisation days* calculated as the total duration in which salinity at the water inlet location exceeds a pre-set legal standard. A 3D hydrodynamic and salt transport model was deemed necessary to compute salinity variations at locations in the estuary. For this purpose, the OSR-model developed by the Port of Rotterdam was chosen. The effects of shallowing on freshwater supply were assessed at two locations in the Nieuwe Maas river, Boerengat and Brienenoordbrug. Some additional post-processing tasks were required to express outcomes from the model in terms of the chosen indicator. In the end, a numerical relation between *bed level change* and *salinisation days* was achieved.

- Port efficiency was assessed through the indicator *average waiting times* of vessels. Also, port capacity was quantified via the *terminal throughput*. To assess effects, the OpenTNSim developed by TU Delft was selected. This model was coupled to the hydrodynamic output from the OSR-model to calculate tidal windows in the port. Then, the effects of shallowing on port performance were assessed in a simplified traffic network for seagoing vessels calling at the Koole terminal, in the 3e Petroleumhaven of the Port of Rotterdam. This assessment resulted in a numerical relation between *bed level change* and *average waiting times*. In all simulations, the *terminal throughput* was remained constant.

3. The individual assessments were combined. Both variables, *salinisation days average waiting times*, were related to each other by the inherent decision variable *bed level change*. As a result, different types of trade-offs were obtained to confront the port network efficiency against the performance of freshwater supply at Boerengat and Brienenoordbrug.

Due to the high number and complexity of the stakeholder interactions in the Rhine Meuse Delta, this study was made as a first approach to show quantitatively how freshwater supply and port-related actors can be related to each other. Unfortunately, interactions with other stakeholders were not considered. Regardless of this simplification, this research found that the comparison tool could find relations amongst more stakeholder interests, such as water safety or nature.

In the objectification process through the FoR approach, it was found that one of the most challenging tasks was designing a measurable quantity related to the operational objective of freshwater supply. Since the objective of each stakeholder depends on many specific interests, it is not easy to represent it via one indicator. In the end, an inevitable mismatch between the objectives and the indicators was accepted. Despite its limitations, the study certainly provides a first comprehensive assessment of multiple effects that, in the terms outlined by the FoR approach, can provide answers concerning nature-based solutions dealing with salt intrusion.

SQ5: What are the effects of shallowing the Rotterdam Waterways on freshwater supply and port logistics objectives, and what is the relation between the impact on these two?

This question is answered in three parts: effects on freshwater supply, effects on port logistics, and the relation between the effects on freshwater supply and port logistics.

Effects on freshwater supply
This study found that shallowing can be associated with a retreat of salt intrusion and thus a beneficial effect on freshwater supply for water inlets located at the Nieuwe Maas. Results indicate that the High Water Slack (HWS) salinity intrusion, computed at the water suction depth of a typical water inlet, can retreat seawards up to 5.5 km (isohaline 70 mg/l) and up to 10 km (isohaline 300 mg/l) for a river bed level increase of + 3.9 m. Moreover, results show that the indicator *salinisation days* decreases gradually as the bed level increase. For both drinking and agricultural water uses, a reduction of up to 100 % could be achieved for a bed level increase of + 3.9 m. Such a reduction indicates that water shortages at the Boerengat water inlet could significantly reduce after shallowing.

Also, numerical relations between *bed level change* and *salinisation days* indicate that a relocation of the Boerengat water inlet to Brienenoordbrug, just 3 km upriver, would decrease water shortages by 35 - 45% without even having to shallow the river. This evidence suggests that the relocation of inlets should be considered a feasible alternative to shallowing or in combination with it.

It is important to highlight that these findings hold for a scenario of low river discharge and mild wind conditions. For other climate scenarios, such as low storms surges or small wind set-up events during the summer (0.5 - 1.0 m), shallowing could have a limited effect on freshwater supply performance. Similarly, the assessment is valid for locations along the Nieuwe Maas. For other locations in the southern part of the estuary (e.g. Spui and Oude Maas river), the effect of shallowing could be lower, or even negligible, compared to water inlets in the northern part.

Finally, a limitation of this study is the assumption of a uniform increase of the bed level in which bed fluctuations are flattened out. To a certain extent, this is unrealistic in the sense that a natural evolution of the bed will likely shape its surface irregularly. As a result, salt transport would be affected by a different topography. Notwithstanding this simplification, this study proved a systematic retreat of salt intrusion while increasing the bed level. For the scope of this research, proving this principle is sufficient to assess the effects of shallowing on freshwater supply.

Effects on port logistics

This research demonstrated that shallowing could impose burdensome accessibility restrictions on the largest vessels calling at a landward seaport in the Port of Rotterdam. This part of the study was designed to determine the effect of shallowing on port efficiency while the terminal capacity remained unchanged. Results indicate that vessels *average waiting times* are in the order of 0.20 hs within a range of bed level increase from +0.0 m to +2.0 m. This is far below the assumed acceptable limit of 11 hs. However, findings indicate that shallowing levels over + 2.0 m lead to an exponential increase of waiting times, which eventually brings the port's service level to an undesired state for a bed level increase of +3.9 m. The increase in waiting times is caused by a rising number of vessels using the network and the access restrictions imposed due to more burdensome tidal windows (horizontal and vertical). Altogether, these findings confirm the hypothesis that the decrease of water depth could result in an inefficient network, harming the port's competitiveness.

It should be noted that the traffic model was highly schematised to a simple network, and assumptions about vessel arrivals and fleet distribution are expected to influence results. Due to the uncertainty emerging from these assumptions, it is not possible to provide accurate answers about the effect of shallowing on port efficiency. Nevertheless, this work was able to determine a general behaviour in the variation of the *average waiting time*, which can be explained by a mild to null decrease followed by an exponential growth while river bed level increases up to +3.9 m.

The insights gained from this study may assist in assessing how shallowing can affect the interaction between port-related actors. Three types of scenarios were considered:

- The exponential growth in waiting times as described before is associated with a scenario in which the shipping agent decides to adapt its fleet loading the network with a large number of small vessels to compensate for the loss of the largest vessels. As a result of large waiting times, the service level of the port is worsened.
- A different situation could occur if the shipping agent chooses to send the largest vessels to competing ports with a better service level. Then, waiting times at the Port of Rotterdam are expected to decrease at the cost of decreasing the terminal's capacity.
- The port could consider relocating terminals to offshore locations where deeper and more capacious nautical infrastructure can be designed. Such a relocation of terminals could occur in future shipping scenarios of fast or slow port energy transition. Assuming a constant throughput, the port's service level could be maintained in both future scenarios. However, the new port configuration could incur significant investment costs for a little-to-null added value in port efficiency and capacity.

This study provided reasons to conclude that shallowing does not seem a promising alternative from the perspective of terminal operators and shipping agents, which greatly influences decision-making by the port authority. However, other trends in future scenarios and other specific aspects in port performance (e.g. sustainable dredging) should be considered, as they might lead to a different conclusion.

Relation between the effects on freshwater supply and port logistics

The comparison tool's final and most important outcome was the quantitative trade-offs between freshwater and port logistics objectives. These relations were shown through four types of graphs combining port efficiency and freshwater supply for drinking and agricultural end-users. They were visualised with salinisation days in the x-axis, average waiting time in the y-axis, and the bed level change as colour-coding. This way, a decision-maker can easily visualise and work on the compromises to be made while moving along the curve.

In all four cases, the curve presents an asymptotic behaviour. It implies that an improvement in towards the objective of freshwater supply always goes to the detriment of port efficiency objectives. The trade-off curves also inform about ranges of values in which this behaviour is less or more pronounced. It was concluded that bed level changes of up to + 2.0 m do not harm port efficiency substantially. However, instead, it increases the performance of freshwater supply via a reduction of shortages in the order of 30-50%. When the bed level increases over the + 2.0 m, a slight improvement in the performance of freshwater supply leads to a rapid deterioration of the port‘s service level, ultimately leading to an unacceptable state when nearing the + 3.9 m bed increase.

Whilst this study cannot be wholly sure about the exact values of the trade-off curves, it substantiates ranges, general trends of losses and gains for end-users quantitatively. Also, how results should be used in policy-making.

To conclude, the pilot implementation in the case study provided evidence demonstrating that the comparison tool applies to nature-based dealing with salt intrusion problems. Through a systematic procedure, indicators obtained from the Frame of Reference (FoR) approach can be related and traded off to each other. This proof-of-concept study validates the comparison tool in a schematised estuary and increases the confidence in applying this tool systematically for more situations. The next section of this chapter mentions the most relevant actions that could be taken towards a broader range of applicability of the tool and a more comprehensive assessment of the estuarine system.

6.1. Recommendations

This section provides two types of recommendations. On the one hand, recommendations for practice and policy-making are provided. On the other hand, suggestions for future research are given from experience gained in developing and implementing the comparison tool. The latter is divided into two parts. The first part deals with general suggestions about the comparison tool, and the second part with recommendations to improve the modelling methodology.

6.1.1. Recommendations for practice and policy-making

This work delivered quantifiable knowledge to support management actions to mitigate salt intrusion in an urbanised delta. This knowledge can be translated to practical implications for freshwater supply and port-related end users, setting a basis for later discussions. Afterwards, these discussions could be part of the agenda to seek a consensus between all stakeholders involved.

- This study found a turning point from which a slight increase of bed level leads to a significant negative effect on port efficiency, whilst the improvement in freshwater supply is limited. If the bed level increases further from this point, a serious conflict of interests between the two types of end-users is expected to emerge. Especially, socio-economical values related to port activities would be largely threatened. Thus, policy-makers are advised to bring attention to the conditions in which this issue can arise.

- Based only on port efficiency and capacity aspects, seeking consensus with port-related actors should be focussed on agreements with the terminal operators, shipping agents, and the port authority. A good business climate for the port partly relies on a sufficient capacity of the terminals and acceptable waiting times of vessels. The project would find great opposition if the shallowing solution cannot meet these requirements.

- Future scenarios in port planning are a key aspect to address the effects of shallowing on port logistics. This study considered changes in traffic flows for a constant throughput. However, more studies concerning an increase or a decrease in throughput should be part of the discussion, as they might lead to different conclusions.

- This work found that the relocation of inlets along the Nieuwe Maas leads to a significant reduction in water shortages (in the order 35 - 45% without even having to shallow the river). Then, a crucial course of action is a comparison of alternatives addressing shallowing measures and relocation of inlets. Since the combination of both measures can reduce water shortages, then freshwater supply objectives could be achieved with a lower shallowing level. This decision could bring the two confronting positions closer in seeking a consensus with port-related end-users.

- As mentioned earlier in the report, this work limited the analysis to freshwater supply and port-related actors. However, a comprehensive study on stakeholder interactions should, at least, consider the following crucial groups of stakeholders:

    1. Water safety-related actors interested in the effects of shallowing on design water levels in the Rhine-Meuse Delta (RMD). It includes the Water Boards and the Rijkswaterstaat.

    2. Environmental organisations aim to understand the potential benefits of shallowing for restoring the natural estuarine ecosystem. This group include both public and private organisations on a national and international scale.

    3. Government, local municipalities (including Rotterdam), and local citizens in the RMD taking a special interest in opportunities for sustainable spatial development in the estuary.

6.1.2. General suggestions about the comparison tool

A natural progression of this work is to analyse how the tool can be further upgraded. To this end, actions are proposed concerning two dimensions: reliability of the outcomes and time-efficiency of the methodology.

Reliability of the outcomes

It is suggested that the comparison tool should incorporate a procedure to validate the strategy in the local context, for instance, through end-users interviews. This information could provide meaningful inputs for formulating strategic and operational objectives correctly. This way, the formulation process could be done an iterating setting [Laboyrie et al., 2018]. Ultimately, the mismatch between end-user‘s operational objectives and the performance indicators could be significantly reduced.

Time-efficiency: towards Multi-Objective Decision Making Problems methods

One of the main concerns identified in this study is the complexity of the modelling methodology if more than two stakeholder objectives are added to the problem. For instance, if a combined assessment between port efficiency, freshwater supply, and environmental aspects is required. Moreover, designers could be interested in understanding the effects of more than one decision variable. For instance, in comprehending the effects resulting from river bed level and width change. This work chose to ‘manually’ couple two modelling studies to assess the effect of one decision variable, which resulted in an efficient approach. However, it is unclear if the methodology would still be time-efficient for more than two stakeholders or one decision variable.

The answers to this challenge could be found in the concepts of *Multi-Objective Decision Making Problems* and *Multiobjective Optimisation* methods. These purely-quantitative methods can relate multiple variables and obtain multi-dimensional trade-offs (even for more than three variables). Moreover, they can fully systematise the combined assessment through computer-based procedures. For more than two stakeholders, the large amount of data to be generated could justify using an automatised approach. In this case, difficulties are foreseen in building a computer-based model that can couple modelling tools for processes with very diversified physical properties spatial and time scales. For instance, to obtain and combine indicators related to processes such as salt transport, traffic flows, or biodiversity development.

6.1.3. Modelling methodology used in the comparison tool

From experience gained in implementing the tool in the case study of the Rotterdam Waterways, suggestions for further improvement of the modelling methodology are given. Upgrades should aim to decrease the uncertainty and develop more comprehensive estuarine models. These improvements are divided into two parts. One relates to the assessment for the freshwater supply system (Table 6.1 and the second to the assessment for the port system (Table 6.2).

Assessment of effects on freshwater supply:

Table 6.1: Set of recommendations to improve the assessment of effects of shallowing on freshwater supply performance.

Recommendation	Intended effect	Remarks
Formulate multiple operational objectives and design indicators for multiple freshwater supply end-user	Decrease the uncertainty of the objective-based assessment process through FoR	Possible additional operational objectives and indicators: a) Daily operation of water inlets: Effect on daily water extraction through the indicator *daily inlet windows duration* b) Deployment of contingency measures during water shortages: Effect on the indicators *duration* and *frequency of exceedance of legal standards*
Increase the spatial scope of the assessment to include other crucial elements of the freshwater supply system in the RMD	More comprehensive modelling methodology	Assess effects of shallowing for water inlets in the southern branches (Spui river, Oude Maas river, Brielse Meer). The analysis should include long-lasting salinisation events due to a ‘post-supply’ phenomena [de Vries, 2014].
Addressing extreme salinisation events related to moderate to high wind boundary conditions	More comprehensive modelling methodology	Investigate on the impact of shallowing on salt transport during salinisation events generated by low storms and small wind set-up events (< 1 m). These conditions can occur during the summer, when the water resource is most needed.
Validate results from the OSR - coarse grid with the OSR - fine grid	Increase reliability in the assessment of salt transport changes	Improve assessment at areas where the river network exhibits complex patterns (e.g. water inlets near confluences H. IJssel/ N. Maas or Lek / Noord/ N. Maas)
Include morphological studies to understand better the bed development of the shallowed river	Include the effect of bed level fluctuations in salt transport	Increase the accuracy of results concerning the effects of shallowing on freshwater supply by using a more realistic irregular topography.

Assessment of effects on port logistics:

Table 6.2: Set of recommendations to improve the assessment of effects of shallowing on port logistics performance.

Recommendation	Intended effect	Remarks
Increase size and complexity of the port network	More comprehensive modelling methodology	1) Add shipping operations and infrastructure to port areas landwards of the 3e Petroleumhaven, and the interaction with shipping operations to the offshore terminals of Maasvlakte and Europoort. 2) Include a landward boundary condition for inland traffic flow connecting the port and the hinterland.
Include AIS data	Reduce uncertainty of model outcomes	More accurate arrival process, fleet size distribution, and variation of vessel speed.
Obtain outputs on a yearly basis and increase the number of runs	Reduce uncertainty of the model outcomes	The number of runs should be bounded to the desired accuracy.
Additional recommendations		
Include port policy indications for vertical and horizontal tidal windows	More comprehensive modelling methodology	Tidal windows calculation closer to real operational restrictions in the PoR.
Add berth allocation feature to the model		Largest vessels can have priority to access deeper berths.
Restrict the number of tugs and pilot assistance		Better estimation of waiting times of vessels.
Include safety margin in the required depth calculation		More accurate tidal window calculation.

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A

Supporting information for the case study

This chapter is set out to present additional infromation about the freshwater and port systems in the Rhine Meuse Delta. It is divided in four parts. Section A.1 is about the freshwater supply system. Section A.2 provides supporting information about estuarine classification. Section A.3 describes the different Salinisation events in the Rhine-Meuse Delta. Finally, Section A.4 provides information about the port system, including information about the Koole terminal and the Port of Rotterdam policy.

A.1. Freshwater supply system in the Rhine-Meuse Delta

Freshwater in the estuary is used for drinking water, agriculture, flushing, industry, and nature. Intakes of water are placed all over the area, with important points along the primary system (Nieuwe Waterweg, Nieuwe Maas, Oude Maas) and the regional system (Hollandsche IJssel, the Lek, the Spui, Hollandse Ijssel). Figure A.1 shows all inlets for drinking and agricultural purposes. The Rhine-Meuse Delta basin, with its most important water inlets, is schematized in Figure A.2.

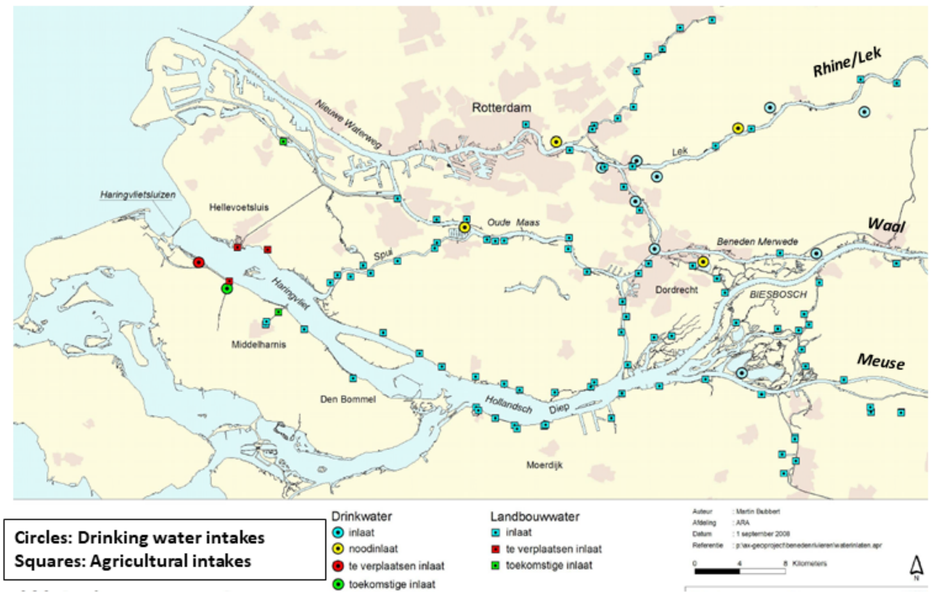


Figure A.1: Map of the freshwater supply system in the Rhine-Meuse Delta (from Rijkswaterstaat).

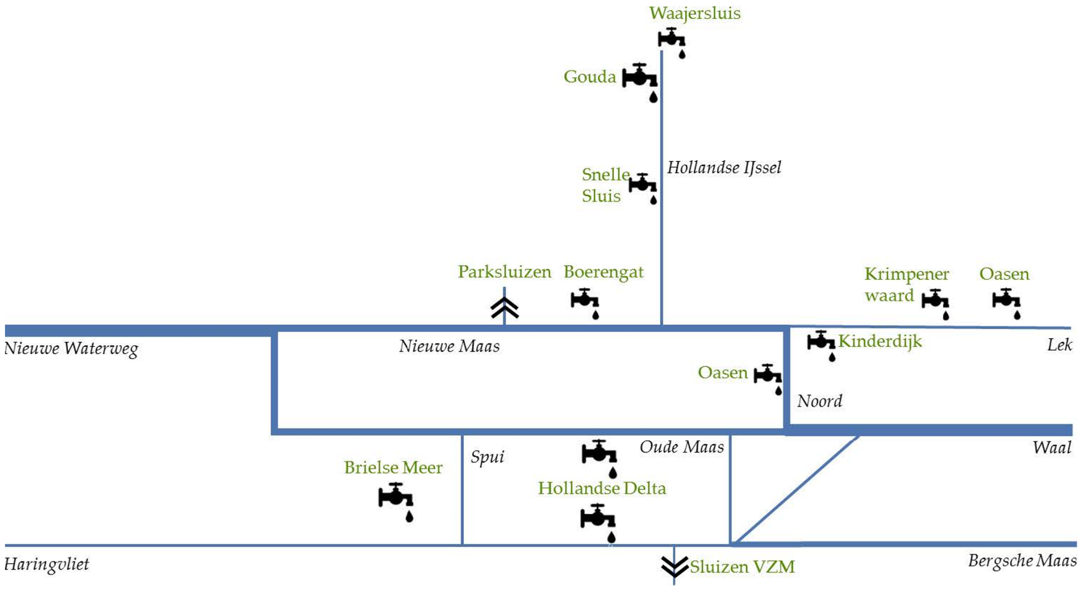


Figure A.2: Schematization of the freshwater supply system in the RMD with the most important water inlets [Hydrologic, 2015]. The thickness of the blue lines is proportional to the discharge distribution during a period of low river run-off i.e. when flow rate measured at Lobith is below 1500 m3/s).

A.2. Estuarine classification

To predict the type of estuary, the Estuary-Richardson number can be used [Pietrzak, 2018]:

$$Ri_E = g\frac{\varepsilon q_f}{u_T^3} \tag{A.1}$$

Where:
ε: relative density difference between two stratified layers, calculated as $\Delta\rho/\bar{\rho}$ with $\Delta\rho$ the density difference and $\bar{\rho}$ the the average density.q_f is the fresh water discharge per unit of width (m^2/s). u_T is the root mean square value of the tidal velocity near the river mouth (m/s). A way to estimate u_T is:

$$u_T = \frac{\hat{u}}{\sqrt{2}} \tag{A.2}$$

Where:
$\hat{u}$: tidal velocity amplitude at mouth (m/s), which can be calculated as $\eta\sqrt{\frac{g}{h}}$, with h the water depth and η the tidal amplitude.

For values below 0.08 the estuary is typically ‘well-mixed’, whereas values above 0.8 are typically for ‘salt-wedge’ estuaries. Values in-between correspond to partially-mixed to stratified estuaries. From the equations above, it can be seen that the Richardson number is proportional to the tidal range to the third power, and to the water depth to the -3/2 power. For a shallowed estuary, it is unclear whether the regime could shift towards a more stratified or to a mixed estuary, as it depends on the degree of shallowing and changes on the propagation of the tide inside the estuary.

Classification of the Rotterdam Waterways

To predict what kind of estuary is in the modelling study, the Richardson number was calculated using the equations above. The following parameters are estimated at the mouth of the Nieuwe Waterweg:
ε: Density differences ($\Delta\rho$) between two stratified layers were found to vary from approximately 0.5 to 5 PSU at sea, leading to $\varepsilon = 4E-4$ to $4E-3$.
$\eta = 0.85m$
$\hat{u} = 0.64m/s$
$u_T = 0.45m/s$

Table A.1: Prediction of estuary classification according to the Richardson number. Estimations are obtained for the Nieuwe Waterweg, as part of the Rotterdam Waterways case study used later on in the modelling study.

	$Q\_f = q\_fW(m^3/s)$	Ri_E lower b.	Ri_E upper b.	Classification
Average discharge ($Q_{Lobith} = 2300m^3/s$)	1456 (63%)	0.153	1.53	Partially-mixed to salt-wedge
Low discharge ($Q_{Lobith} = 1000m^3/s$)	900 (90%)	0.094	0.94	Partially-mixed to stratified

$h = 17.2m$
$W = 500m$ (width at the mouth)

For average conditions, the river discharge at the Nieuwe Waterweg is assumed to be 63.3% of the discharge measured at Lobith. For low river discharge conditions ($Q_{Lobith} < 1100m^3/s$) the Haringvliet sluices are closed [ter Maat, 2015]. As a reference value, ter Maat [2015] uses a discharge of 882 (m^3/s) at the Nieuwe Waterweg corresponded to 980 (m^3/s) measured at Lobith. It results in a proportion of 90.0%.

For the low river discharge scenario, the Rhichardson number is close to the ‘well-mixed’ value of 0.08. This could indicate a shift to a well-mixed regime during weak stratification periods.

For the average discharge scenario, this estimation shows that the estuary can be in the salt-wedge regime. However, this could not be confirmed in literature. More comprehensive types of classifications, such as the one by Geyer and MacCready [2014], shows that the estuary falls under a partially-mixed to stratified estuary [Kranenburg and van der Kaaij, 2019].

A.3. Salinisation events in the Rhine-Meuse Delta

Different types of sanitisation can occur in the RMD depending on the environmental conditions [ter Maat, 2015]. de Vries [2014] describes four types of salinisation events:

- **Type 0):** At extremely low river discharge (<1500 m3/sec at Lobith) and normal tidal conditions (i.e. without wind set-up), the salt tongue in the Nieuwe Waterweg can penetrate further upstream. This form of salinization is a threat to the fresh water intake points at the northern edge of the Rhine-Meuse Delta (Hollandsche IJssel, Lek), but not for the southern edge (Spui, Haringvliet, and Hollandsch Diep). This event has a time scale of weeks to months.

- **Type 1):** Due to a combination of low river discharge and storm surges, salinity peaks occur in the order of 1-2 tides. During the event, tidal flow via Nieuwe Waterweg and Oude Maas penetrates through the Spui, even causing salt intrusion in the southern branches.

- **Type 2):** After the salinity peak of event Type 1, the southern branches are salinised. However, the Haringvliet sluices are closed because river discharge is below the normative, thus, salt can only be flushed out back to the sea northwards through the Spui-Oude Maas-N. Waterweg. This is gradual process called ‘post-supply’, and it can last for weeks until salt concentrations restored to normal conditions. Usually, both types 1 and 2 occur during autumn or winter.

- **Type 3):** Prolonged low river discharge levels can cause a gradual increase of the chloride concentration of the river side. This process can take months to occur.

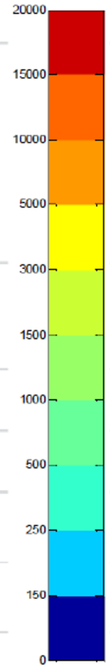
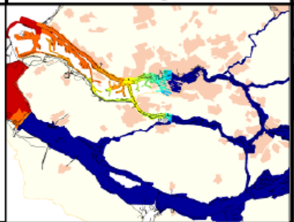
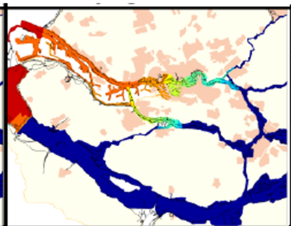
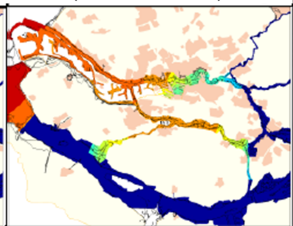
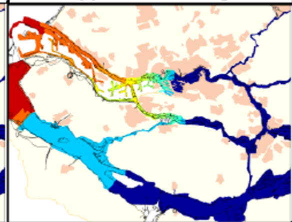
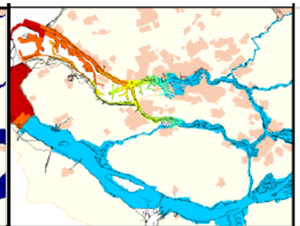
Verziltings type	_	0	1	2	3	Schaal (mg Cl/l)
Omschrijving	Average conditions	Low river discharge and normal conditions	Low river discharge and storm surge (Winter/autumn)	Prolonged backward salinisation after type 1 event	backward salinisation due to high river concentrations	
Zout verspreiding						
Tide	gemiddeld	normaal	forse getijopzet waarbij de vloedstroom richting Haringvliet langer dan één getijperiode kan aanhouden	normaal	normaal	
River discharge	gemiddeld	laag	normaal/laag	laag	extreem laag	
Periode	jaarrond	jaarrond	najaar/ winter	najaar/ winter	zomer/ najaar	
North edge	0	+	++	0	+	
South edge	0	0	++	++	+	
Duur	1 getij	weken - maanden	2 getijden	weken - maanden	weken - maanden	
Frequentie	Groot deel van het jaar	Jaarlijks	Eens in de 5 jaar	Eens in de 10 jaar	Eens in de 3 jaar: huidig ≤ 130 mg/l toekomstig ≥ 150 mg/l	

Figure A.3: Salinisation events in the Rhine-Meuse Delta according to de Vries [2014]. The figures and content of the table is based on Kranenburg [2015].

A.4. Port system

A.4.1. Koole terminal

Figure A.4: Koole terminal layout, including jetties and quay walls infrastructure (identification in red text).

Table A.2: Koole terminal description according to the harbour chart [Port of Rotterdam Authority, 2021].

Terminal id	Type of terminal	MBL (in NAP m)	MBL (in LAT m)	Mooring facility	Length (m)
KOOLE KADE 11	Deepsea	-12.65	11.85	Quay	250
KOOLE KADE G EN H	Coaster	-8.15	7.35	Quay	253.5
KOOLE 10 BIN	Coaster and IWT	-8.15	7.35	L jetty	140
KOOLE 10	Deepsea	-17	16.2	L jetty	395
KOOLE 9	Deepsea	-12.65	11.85	L jetty	250
KOOLE 9 BINNEN	IWT	-	-	L jetty	132
KOOLE 9 KADE	IWT	-	-	Quay and L jetty	132
KOOLE KADE C	IWT	-	-	Quay and T jetty	162
KOOLE 7 BINNEN	IWT	-12.65	11.85	T jetty (southern arm)	162
KOOLE 7 BUITEN	Deepsea and IWT	-15.9	15.1	T jetty (southern arm)	222
KOOLE KADE B	IWT	-	-	Quay and T jetty	110
KOOLE 6	Deepsea and IWT	-15.9	15.1	T jetty (northern arm)	253
KOOLE KADE A	IWT	-	-	Quay and T jetty	132

A.4.2. Port of Rotterdam policy

FWA and UKC policy

The PoR policy stipulates the Freshwater Allowance (FWA) and Underkeel Clearance (UKC) which varies by areas within the port. In this section, only the information that is relevant for the traffic modelling study is included. For more information, the reader is referred to the Appendix B in de Jong [2020] based on design guidelines by the Port of Rotterdam Harbour Master's Division (DHMR).

The UKC policy for the Nieuwe Waterweg, Nieuwe Maas, and Oude Maas is 10% of the vessel's nominal draught. For the Botlek and city port areas, it is 0.5 m.

The FWA along the Nieuwe Waterweg, between the mouth and the river section km-raai 2022, is 1% of the nominal vessel draught. Landwards of that river section it is 2.5% of the nominal vessel draught.

Accessibility conditions

Accessibility should be provided for 99% of the tidal cycles (often during high tides) for tide-bound vessels and 99% of the time for non-tide-bound vessels.

B

Numerical modelling study - Salt intrusion

This Appendix provides additional information concerning the modelling study on salt intrusion.

B.0.1. Numerical modelling choice

The model selection is usually a trade-off between the expected accuracy and the computational effort required to carry out the simulations. The computational power available to conduct this research was a limiting factor. The availability of models for the case study is also a limiting factor, although there are many options to study salt intrusion in The Netherlands.

On the one hand, 1D are low computational effort tools, which means simulations can be done for an extended period. However, salt transport is highly dependent on horizontal and vertical dispersion mechanisms, which a 1D approach typically reduce these two to a single dispersion coefficient. This coefficient should be validated for case-specific conditions. Examples of models applied in The Netherlands are SOBEK-RE NDB 110 as part of the Delta Model. However, measures such as river bed elevation are highly uncertain and might affect the model parameterisation and result [Prinsen et al., 2014].

On the other hand, it was evaluated whether three-dimensional (3D) are suitable. The advantage is that it represents the physics much better, particularly in including mixing processes caused by effects from the port basins and interaction between river branches. Salt intrusion in estuaries is highly dependent on 3D physical phenomenon [Geyer and MacCready, 2014]. The disadvantage of a 3D model could be the rather high computational effort. In the Rhine-Meuse estuary, the closest example is the 3D Operational Flow Model Rotterdam (OSR), a flow model based on TRIWAQ TRIWAQ developed by the Rotterdam Port Authority. The model has been developed primarily to support port operations but is also used for salinisation studies. A few years ago, Deltares carried out an evaluation of the OSR commissioned by Rijkswaterstaat [Kranenburg, 2015]. As a result of this evaluation, the model has been further improved and re-validated and is considered one of the best available models to assess effects in the Rhine Meuse Delta. For instance, this model was used to study the effects on salt intrusion and freshwater availability for the deepening project of the Niuewe Waterweg and Botlek area [Hydrologic, 2015]. Also, it was the preferred choice to study the effects of shallowing of the Oude Maas river [Huismans and Plieger, 2019]. Other examples include the stratification induced by opening of Haringvliet sluices [Binsma, 2021], salt intake via the Haringvliet sluices (Kierbesluit), flushing the Hollandsche IJssel with fresh water, and allowing tidal action in the Volkerak-Zoommeer.

The OSR model schematisation is available in two grid resolutions: ‘NSC-Fine’ and ‘NSC-coarse’. It should be noticed that all practical applications with the OSR model were carried out with the fine-resolution grid, which is around three times more refined than the NSC-coarse. Also, it requires at least ten times more simulation time with high computational power (see Table B.1). The Port Authority commonly uses the NSC-coarse scheme to predict water and salt transport for yearly simulations. It is an efficient tool that can be coupled to models for long-term morphologic development (personal communication from Lamber Hulsen, Port of Rotterdam). In the case of wide estuaries (width »> depth) with irregular bed bathymetry, such as the Rotterdam Waterways (650-2500m > 6-17m), lateral and vertical mixing processes may play an important role in the up-estuary salt intrusion. Whilst the OSR-fijn model has proven to have a locally refined grid and accurate bathymetry description, previous works studying salt intrusion with the OSR-Grof (coarse) model were not found in the literature. Accepting this uncertainty and considering the available computational resources, the OSR NSC-coarse is the most suitable model to quantify chloride concentrations for reference locations. In that sense, this model is deemed to be sufficient for a proof-of-concept study.

Table B.1: Decision parameters for the 3D schematizations OSR-Fijn and OSR-Grof. For the OSR-Fijn model, the work by [Binsma, 2021] was taken as a reference. Both models schematizations can reproduce hydrodynamics and salinity in the estuary.

	OSR-Fijn	**OSR-Grof**
Computational resources	Intel Core i7 Processors	20 processors - Linux remote SSH Beowulf type cluster
Average real time per simulated day	0.04-0.05	0.4
Horizontal grid size	7 cells width in the Nieuwe Waterweg	20 cells width in the Nieuwe Waterweg
Vertical grid	10 layers (not equidistant)	10 layers (not equidistant)

B.0.2. Bathymetry

To be able to determine the effect of shallowing from the current situation, it has been chosen to work with the latest schematization, in which the execution of Maasvlakte II, the Nieuwe Waterweg deepening, and adjustments to the Breediep and the Botlek have been incorporated. Schematization and model version details are shown in Table B.2. To follow up, the bathymerty maps are presented in Figures B.1 to B.5.

Table B.2: Detail of model schematizations and versions.

–	**OSR Harbour HA01**	**OSR NSC Grof NG03**
Version	2020_v101	2020_v101
Last adjustment date	20/03/2020	23/03/2020
Reference bathymetry	bathymetry_HA01_2019_v102_ Verdiepte_NWW_Botlek_aug	bathymetry_NG03_2019_v102_ Verdiepte_NWW_Botlek_aug
Shallowing up to -15.0 m	bathymetry_NG03_2019_v102_ Verdiepte_NWW_Botlek_aug _shallow_15	bathymetry_NG03_2019_v102 _Verdiepte _NWW_Botlek_aug _shallow_15
Shallowing up to -14.5 m	bathymetry_NG03_2019_v102 _Verdiepte _NWW_Botlek_aug _shallow_14.5	bathymetry_NG03_2019_v102 _Verdiepte_NWW_Botlek_aug _shallow_14.5
Shallowing up to -13.5 m	bathymetry_NG03_2019_v102 _Verdiepte _NWW_Botlek_aug _shallow_13.5	bathymetry_NG03_2019_v102 _Verdiepte_NWW_Botlek_aug _shallow_13.5
Shallowing up to -12.5 m	bathymetry_NG03_2019_v102 _Verdiepte _NWW_Botlek_aug _shallow_12.5	bathymetry_NG03_2019_v102 _Verdiepte_NWW_Botlek_aug _shallow_12.5

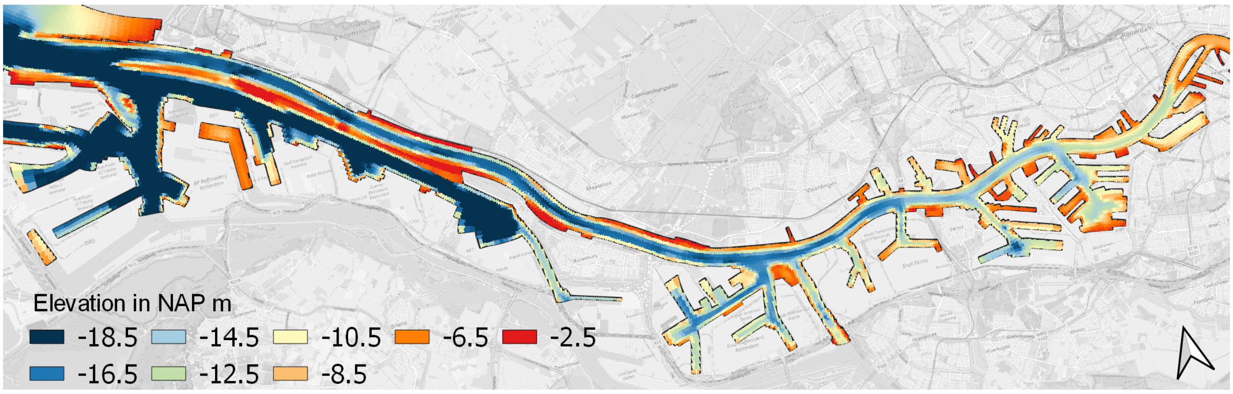


Figure B.1: Bathymetry for the reference state.

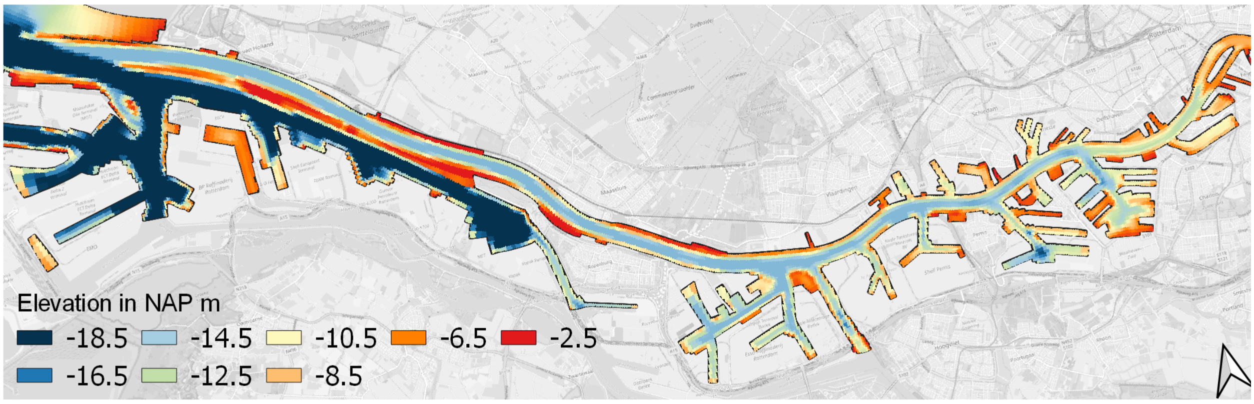


Figure B.2: Bathymetry for the shallowing up to NAP -15.0 m. Shallowed areas are depicted in dark blue. The colour bar of this figure was adjusted so that shallowed areas can easily be viewed.

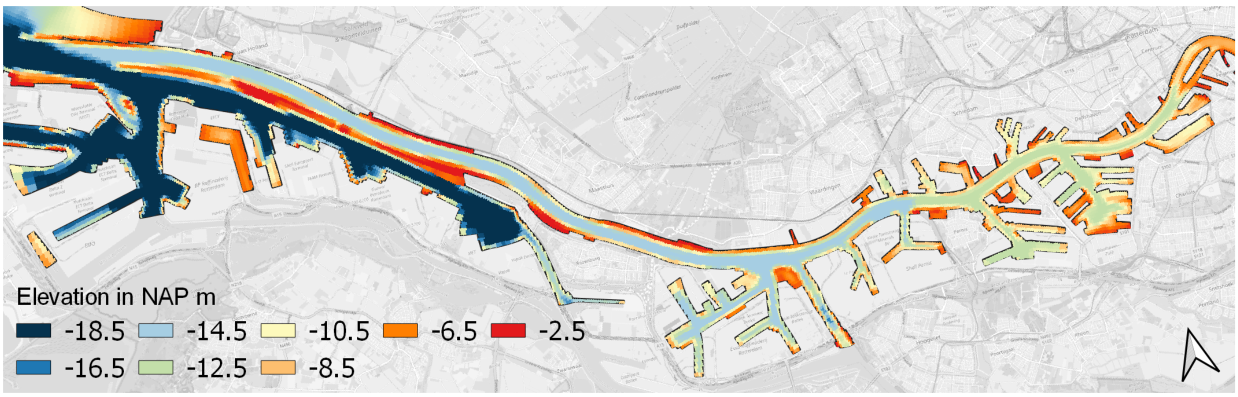


Figure B.3: Bathymetry for the shallowing up to NAP -14.5 m. Shallowed areas are depicted in dark blue. The colour bar of this figure was adjusted so that shallowed areas can easily be viewed.

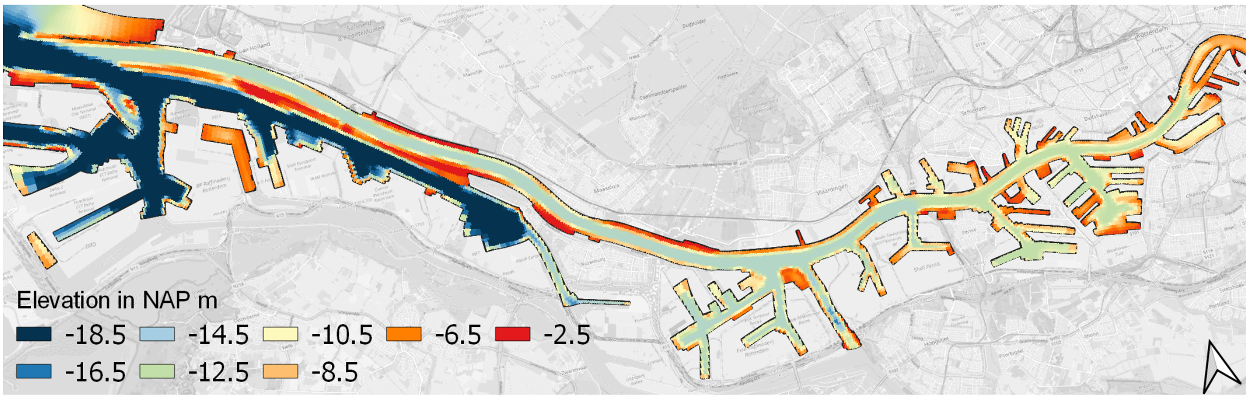


Figure B.4: Bathymetry for the shallowing up to NAP -13.5 m. Shallowed areas are depicted in dark blue. The colour bar of this figure was adjusted so that shallowed areas can easily be viewed.

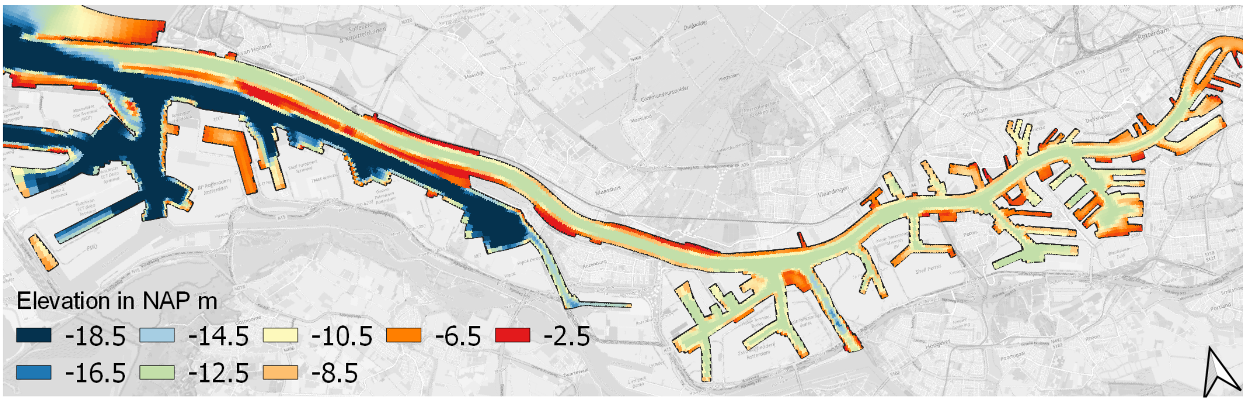


Figure B.5: Bathymetry for the shallowing up to NAP -12.5 m. Shallowed areas are depicted in dark blue. The colour bar of this figure was adjusted so that shallowed areas can easily be viewed.

B.0.3. Vertical grid

The OSR schematization use the software TRIWAQ for the 3D model. This model use a terrain-following discretization of the vertical dimension, also know as sigma-layering. It means the vertical grid lines are not equidistant, but it is more refined near the bottom than near the surface, such that salinity transport is better reproduced in the lower part. layer = 1 : thickness = 12.0 perc
layer = 2 : thickness = 12.0 perc
layer = 3 : thickness = 11.0 perc
layer = 4 : thickness = 11.0 perc
layer = 5 : thickness = 11.0 perc
layer = 6 : thickness = 11.0 perc
layer = 7 : thickness = 11.0 perc
layer = 8 : thickness = 9.0 perc
layer = 9 : thickness = 6.0 perc
layer = 10 : thickness = 6.0 perc

B.0.4. Boundary conditions and hydraulic structures

The OSR schematization use the software WAQUA for the 2D model. The model requires boundary conditions of flow and salt transport at the sea and river edges (see Figure B.6). Boundary conditions at the sea side are divided in three edges, on which water level, velocity, and salinity are defined (see Table B.3). Boundary conditions at the river edges are the discharge and the background salinity (see Table B.4).

Also, the model includes the operation of all relevant hydraulic structures for flow regulation, flood safety, and shipping as internal boundaries (Table B.5).

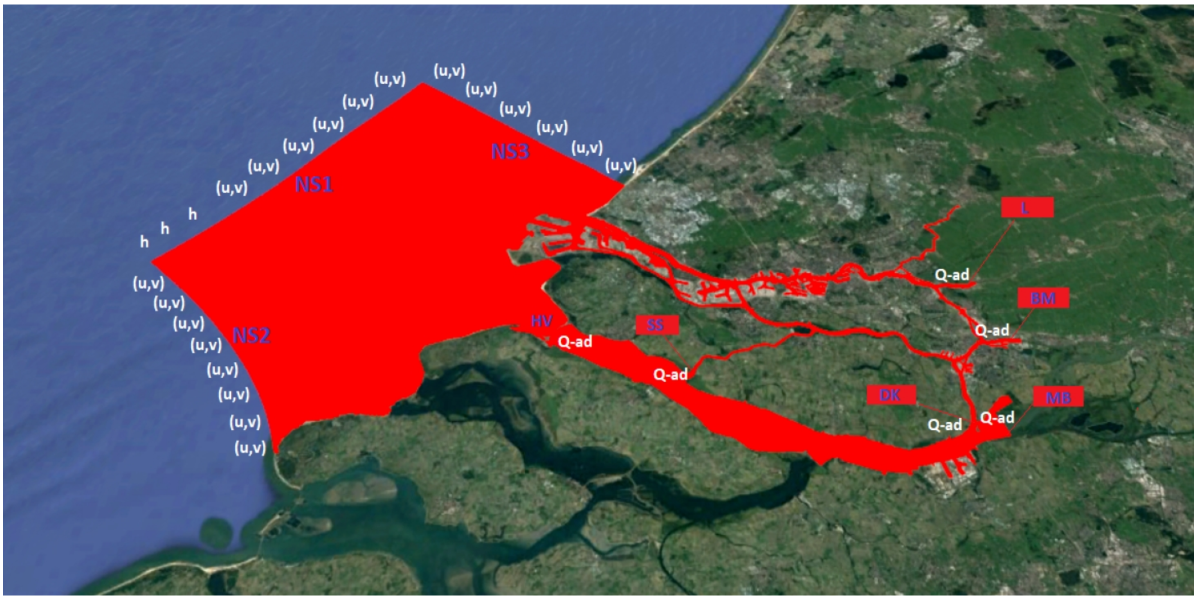


Figure B.6: OSR-HV flow and transport boundary conditions (by courtesy of J. Binsma, from [Binsma, 2021]). L: Lek; DK: Dordtsche Kil; HV: Haringvliet; SS: Spui South; BM: Ben. Merwede; NS: North Sea; MB: Moerdijk bridge. Where river sections are indicated as ‘Q-ad’ there is an automatic distribution of discharge over the cross-section, so that higher flow velocities are found in the main channel part. Velocities boundary conditions in the North Sea are indicated as ‘(u,v)’ and water levels as ‘h’.

Table B.3: Boundary conditions at the sea side.

Boundary	Location	Flow	Salt transport
NS boundary 1	Offshore	Riemman bound. conditions[1]	35 PSU
NS boundary 2	South	Riemman bound. conditions[1]	Gradient near-to-offshore 28-35 PSU
NS boundary 3	North	Riemman bound. conditions[1]	Gradient off-to-nearshore 35-28 PSU

[1] Derived from real measurements in 2014.

Table B.4: Boundary conditions at the river side.

Location	Flow	Salt transport
Lek	159 m3/s	0.13 PSU
Waal	697 m3/s	0.13 PSU
Maas	169 m3/s	0.07 PSU

Table B.5: Internal boundaries in the OSR-HV model.

Hydraulic Structure	Location	Type
Maeslantkering	Nieuwe Waterweg	Flood safety
Hollandsche Ijssel Lock	Hollandsche Ijssel	Shipping
Hollandsche Ijssel Barrier	Hollandsche Ijssel	Flood safety
Rozenburg Lock	Caland channel	Shipping
Hartel Lock	Hartel channel	Shipping
Haringvliet Sluices (x17)	North Sea	Flood safety
Hartel Barrier North	Hartel channel	Flood safety
Hartel Barrier South	Hartel channel	Flood safety

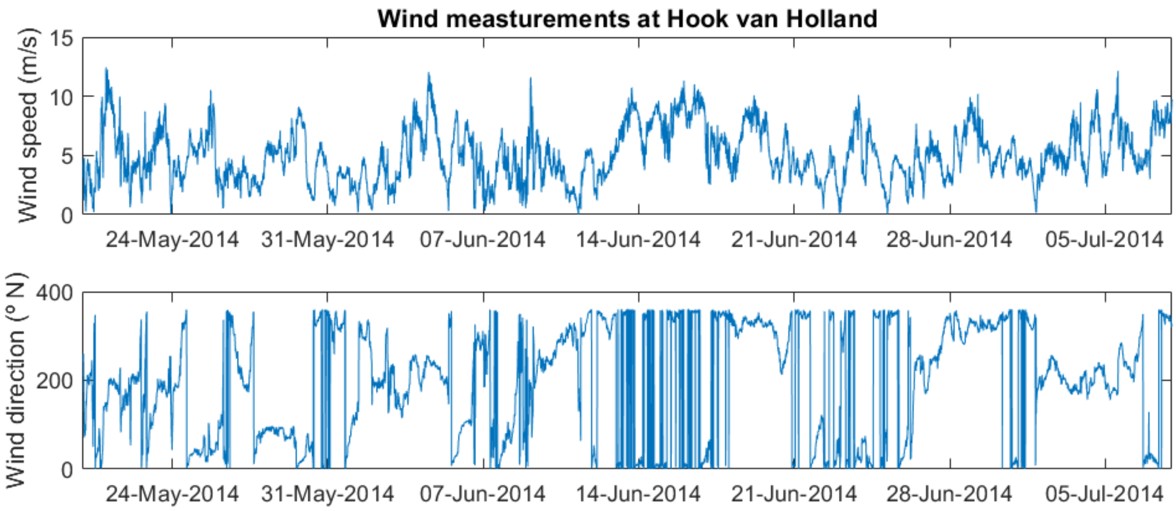


Figure B.7: Wind boundary conditions used in the OSR-model. The upper plot shows the wind direction, and the lower plot presents the wind speed. As seen from the figure, wind is most of the time below 10 m/s.

B.0.5. Initial conditions

The variables that need to be know at the start of the simulation are the horizontal flow velocity, water levels, and salinity. In all simulations, initial conditions corresponded to the state on the 1st of January of 2021.

B.0.6. Additional model settings

General:
Manning coefficient of 0.020 $m^{-1/3}$s in both horizontal directions
Gravity = 9.813 m/s2
Water density = 1023.0 kg/m3
Air density = 1.205 kg/m3
Global diffusion coefficient = 0.01 m2/s
Wind stress coefficient = 0.0026 Reference density = 1.00
Water temperature = 10 °C

Flow
Eddy viscosity coefficient = 1.00 m2/s
Time step = 0.5 min
Max. iterations continuity (itercon) = 40
Max. iterations momentum (itermom) = 20
Convergence criterion vel.(iteraccurvel) = 0.0005
Implicitness parameter (theta) = 0.5
Smoothing (tlsmooth) = 0.0

Transport
Implicitness parameter (theta) = 0.6148
Anticreep = 'on'

B.1. OSR model results

This section presents additional information and visualizations about the outcomes from the hydrodynamic and salt transport model.

Spin-up time
It is observed that spin-up time for flow is relatively fast. Spin-up is usually in the order of 1-2 tidal periods. However, salt transport requires a much longer time to adapt to the boundary conditions. A spin-up time of 14 days is chosen from the 12-05 to the 26-05 (see Figures B.8 and B.9).

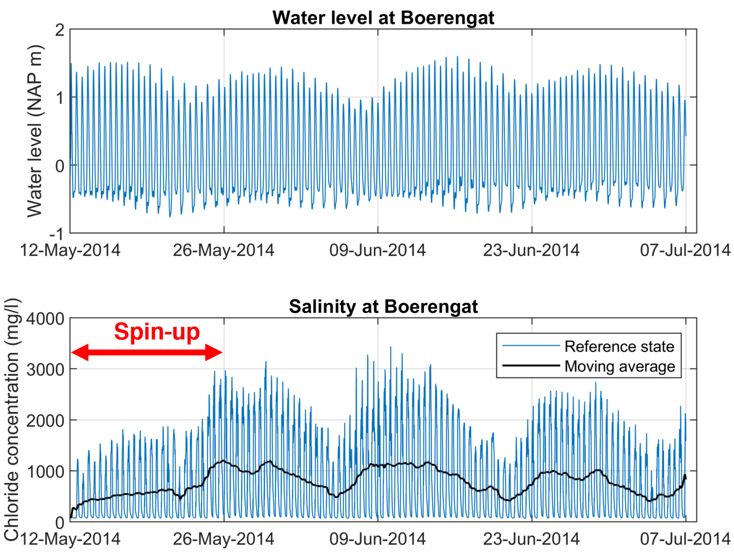


Figure B.8: Chloride content time series obtained with the OSR model at the Boerengat water inlet. The time series corresponds to the reference case. The figure shows the 10 min time step signal in blue and the moving average calculated over two tides (24.8) in black. The spin-up time is estimated from the 12-05 until the 26-05.

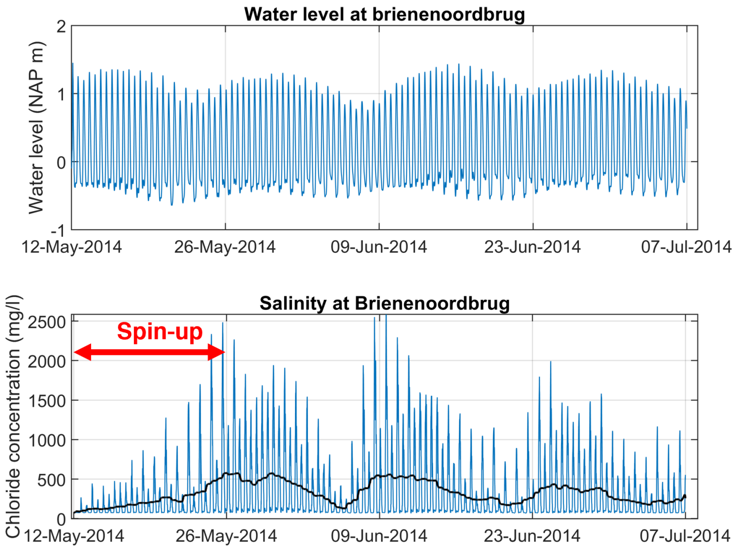


Figure B.9: Chloride content time series obtained with the OSR model at Brienenoordbrug. The time series corresponds to the reference case. The figure shows the 10 min time step signal in blue and the moving average calculated over two tides (24.8 hs) in black. The spin-up time is estimated from the 12-05 until the 26-05.

B.1.1. Effect of shallowing on the hydrodynamics

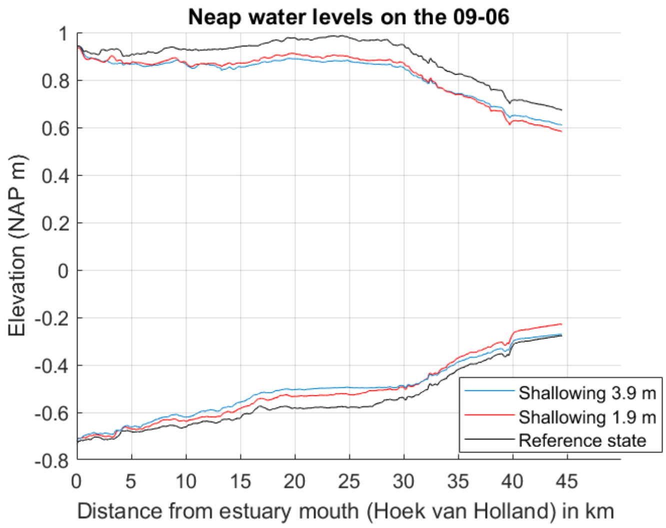


Figure B.10: Longitudinal variation of the water level along the Nieuwe Waterweg and Nieuwe Maas during spring tide. The seaward edge is Hoek van Holland (km 1032) and the land ward edge is at the confluence with the Lek river. The figure shows the water level at two different moments on the same day (24-06). The spring high water at 13:00 hs and the spring low water at 21:00 hs.

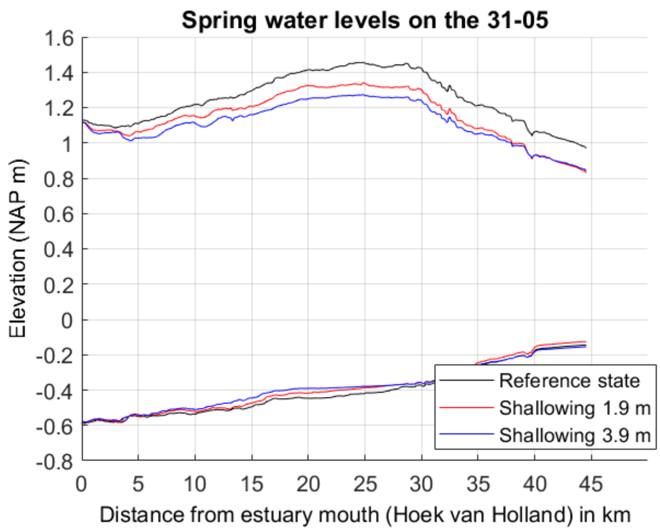


Figure B.11: Longitudinal variation of the water level along the Nieuwe Waterweg and Nieuwe Maas during neap tide. The seaward edge is Hoek van Holland (km 1032) and the land ward edge is at the confluence with the Lek river. The figure shows the water level at two different moments on the same day (09-06). The spring high water at 11:00 hs and the spring low water at 05:00 hs.

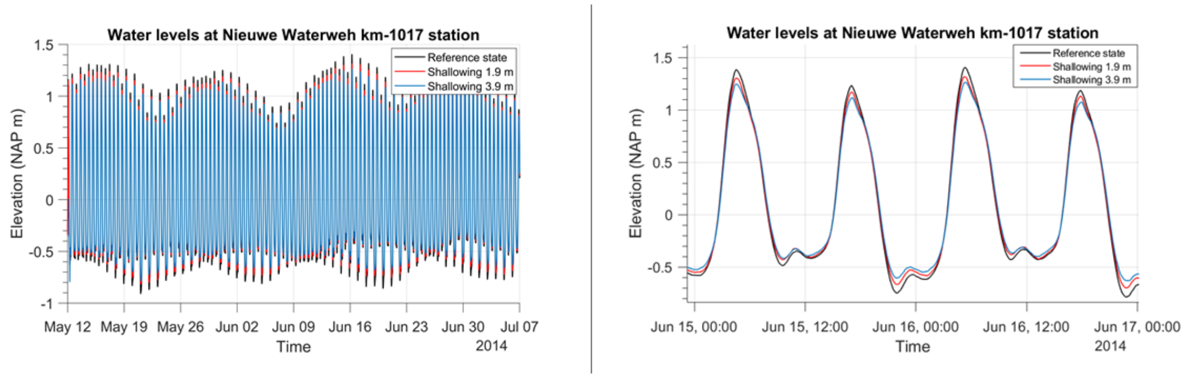


Figure B.12: Left: Time series of the water level computed at the controlling station on the Nieuwe Waterweg km-1017, for different bed levels. The simulation was conducted for a period without wind set-up. The total simulation time is 42 days. Right: The figure shows an expansion of the time series for the period between the 15-06 and 17-06.

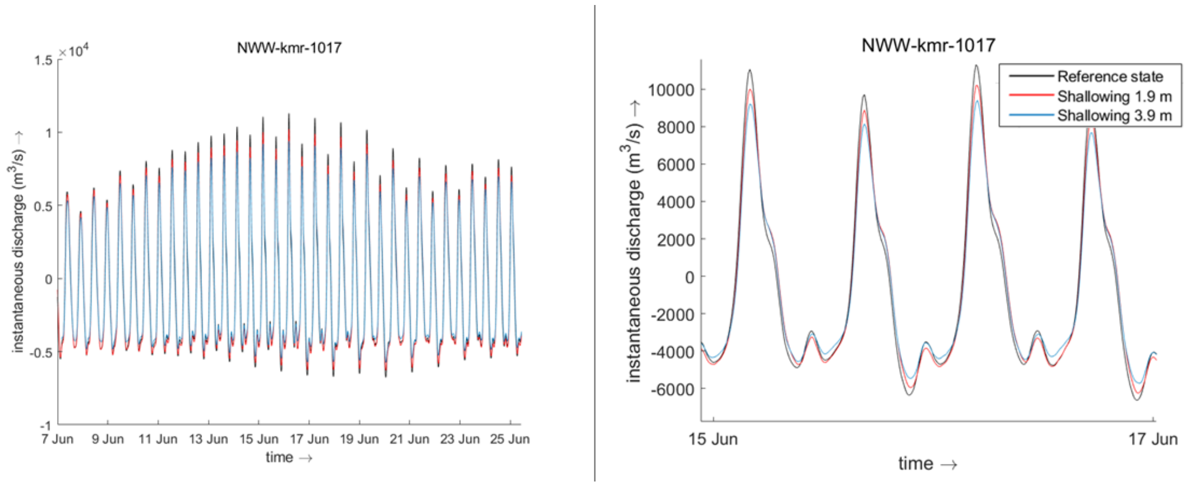


Figure B.13: Left: Time series of the tidal flow discharge amplitude computed at the controlling station on the Nieuwe Waterweg km-1017, for different bed levels. Right: The figure shows an expansion of the time series for the period between the 15-06 and 17-06.

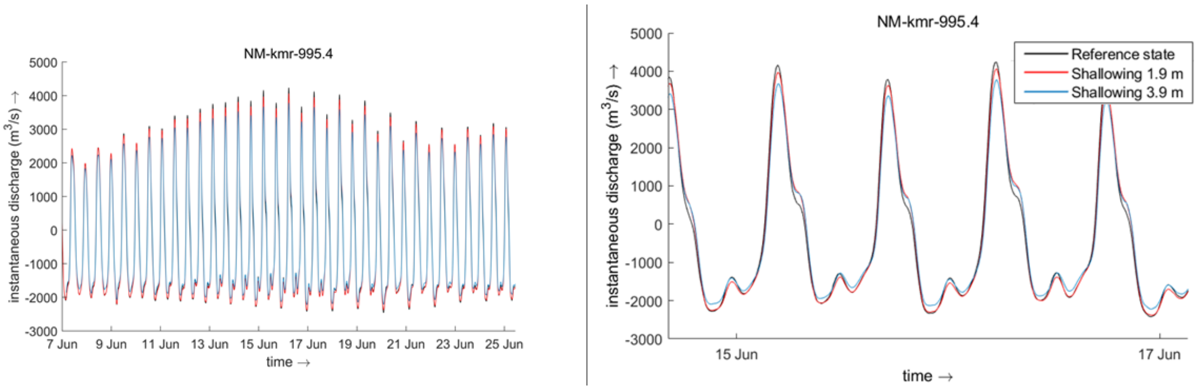


Figure B.14: Left: Time series of the tidal flow discharge amplitude computed at the controlling station on the Nieuwe Maas km-995, for different bed levels. Right: The figure shows an expansion of the time series for the period between the 15-06 and 17-06.

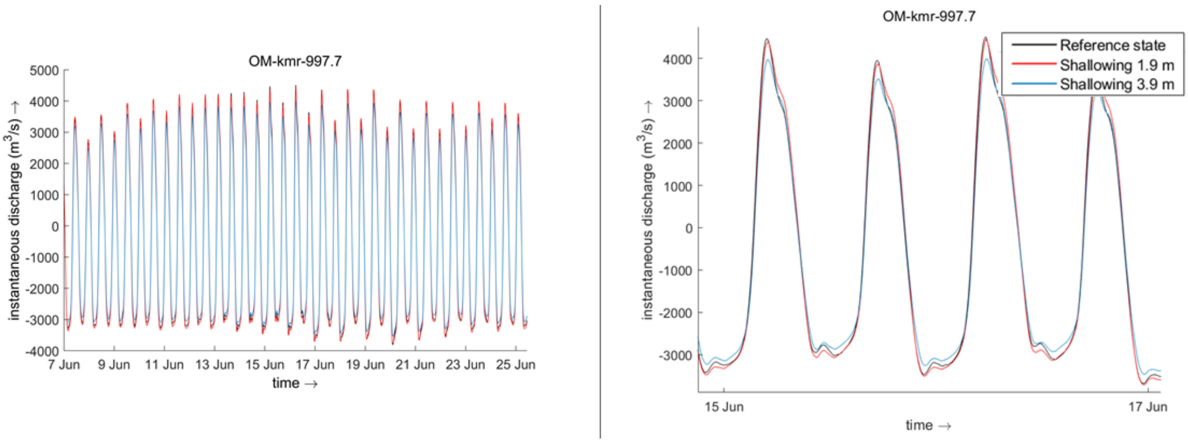


Figure B.15: Left: Time series of the tidal flow discharge amplitude computed at the controlling station on the Oude Maas km-997, for different bed levels. Right: The figure shows an expansion of the time series for the period between the 15-06 and 17-06.

B.1.2. Salinity maps

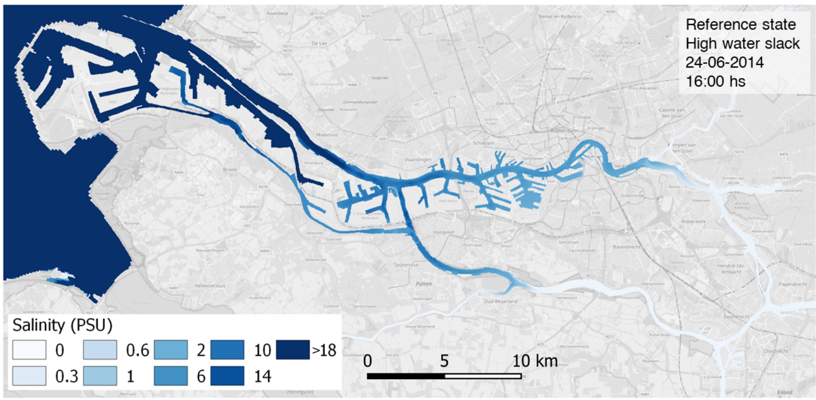


Figure B.16: Salinity map of the Rhine-Meuse estuary during High Water Slack. The figure shows results from the OSR-model for the reference state (no changes in bed level). Environmental conditions correspond to low river discharge (1000 m3/s at Lobith) and mild wind conditions (below 10 m/s). The degree of salinity (in PSU) is depicted in blue color coding. The darker the blue colour, the higher the salinity. As seen from this figure, salinity values over 0.3 PSU reaches up to the area near Krimpen aan de Lek in the northern part of the estuary, and up to Oud Beijerland in the southern part.

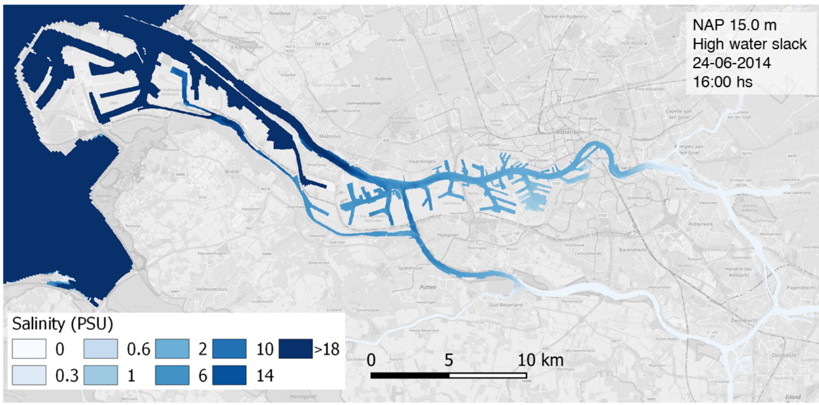


Figure B.17: Salinity map of the Rhine-Meuse estuary during High Water Slack. The figure shows results from the OSR-model for the shallowing NAP -15.0 m state (+1.4 m). Environmental conditions correspond to low river discharge (1000 m3/s at Lobith) and mild wind conditions (below 10 m/s). The degree of salinity (in PSU) is depicted in blue color coding. The darker the blue colour, the higher the salinity. As seen from this figure, salinity values over 0.3 PSU are slightly shifted seawards compared to Figure B.16.

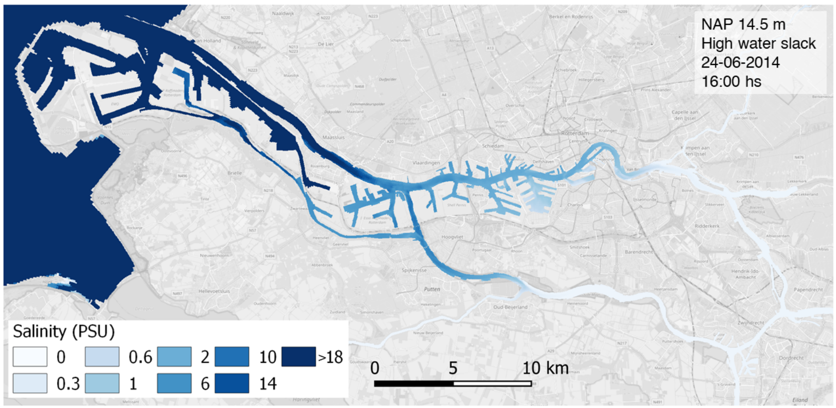


Figure B.18: Salinity map of the Rhine-Meuse estuary during High Water Slack. The figure shows results from the OSR-model for the shallowing NAP -14.5 m state (+1.9 m). Environmental conditions correspond to low river discharge (1000 m3/s at Lobith) and mild wind conditions (below 10 m/s). The degree of salinity (in PSU) is depicted in blue color coding. The darker the blue colour, the higher the salinity. As seen from this figure, salinity values over 0.3 PSU reaches up to the confluence with the Hollandsche IJsell in the northern part of the estuary, and up to Oud Beijerland in the southern part.

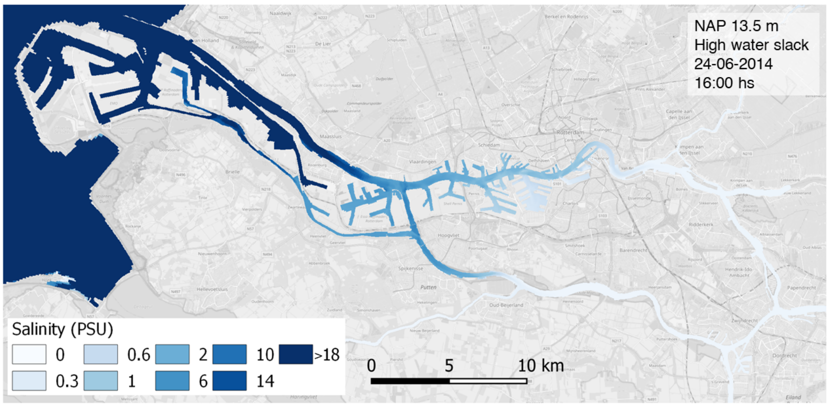


Figure B.19: Salinity map of the Rhine-Meuse estuary during High Water Slack. The figure shows results from the OSR-model for the shallowing NAP -13.5 m state (+2.9 m). Environmental conditions correspond to low river discharge (1000 m3/s at Lobith) and mild wind conditions (below 10 m/s). The degree of salinity (in PSU) is depicted in blue color coding. The darker the blue colour, the higher the salinity. As seen from this figure, salinity values over 0.3 PSU reaches up to Brienenoordbrug in the northern part of the estuary, and up to confluence Oude Maas/Spui in the southern part.

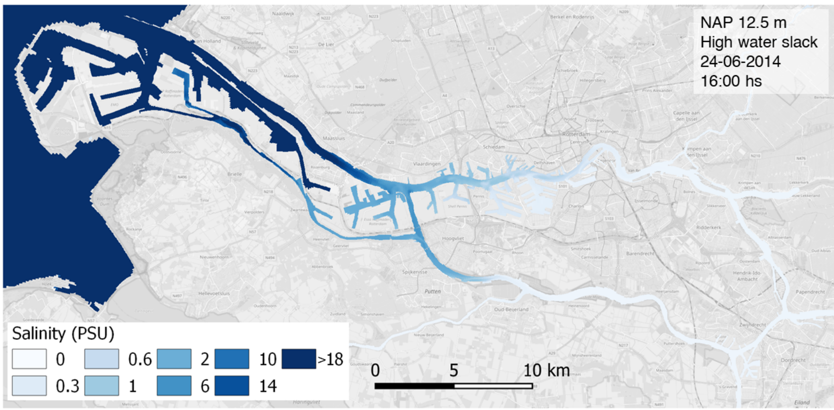


Figure B.20: Salinity map of the Rhine-Meuse estuary during High Water Slack. The figure shows results from the OSR-model for the shallowing NAP -12.5 m state (+3.9 m). Environmental conditions correspond to low river discharge (1000 m3/s at Lobith) and mild wind conditions (below 10 m/s). The degree of salinity (in PSU) is depicted in blue color coding. The darker the blue colour, the higher the salinity. As seen from this figure, salinity values over 0.3 PSU reaches near Boerengaat in the northern part of the estuary, and slightly down the Oude Maas river in the southern part.

B.1.3. Effect of shallowing on salinity concentrations at study locations

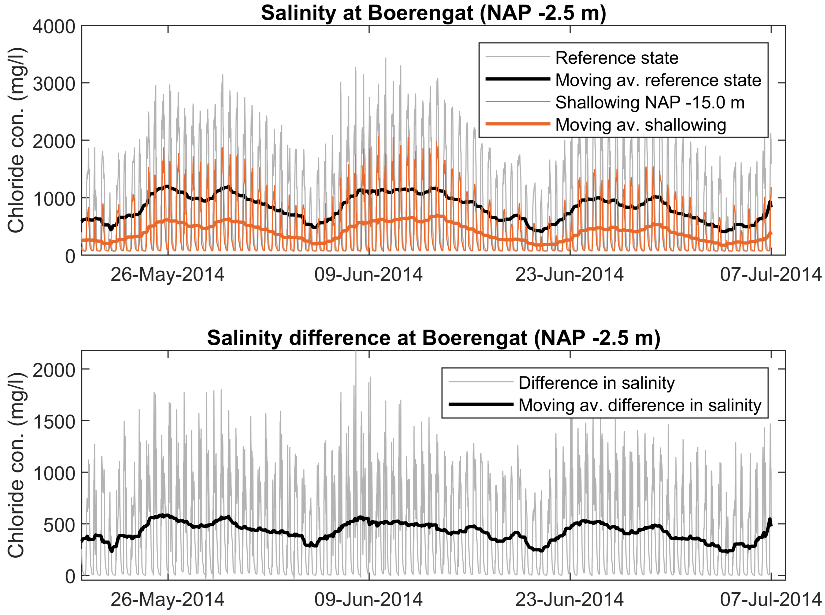


Figure B.21: Impact of shallowing NAP -15.0 m on chloride concentration at Boerengat. Values are computed at a water depth of approximately NAP -2.5 m, since this is the water inlet suction depth. The figure shows the 10 min time step signal for the reference and shallowing state, and the corresponding moving averages calculated over two tides (24.8 hs).

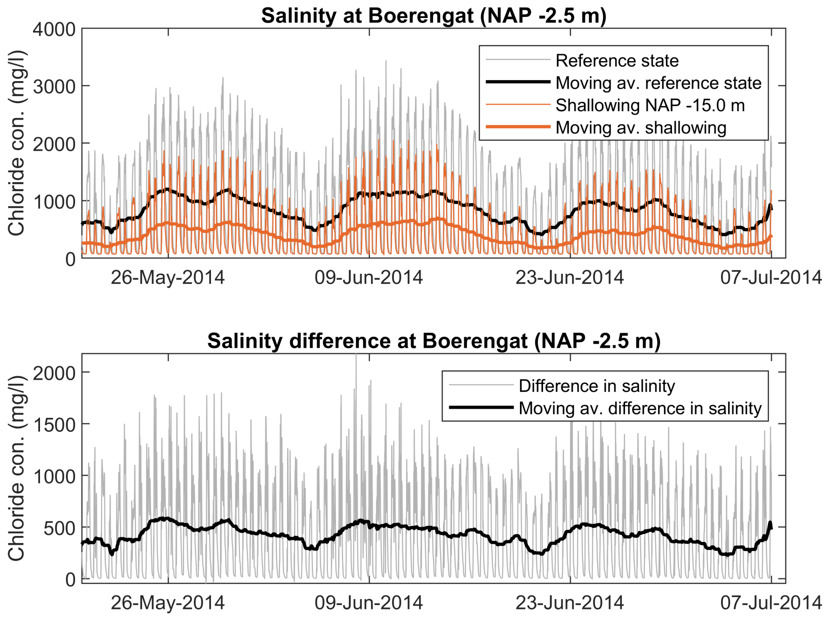


Figure B.22: Impact of shallowing NAP -14.5 m on chloride concentration at Boerengat. Values are computed at a water depth of approximately NAP -2.5 m, since this is the water inlet suction depth. The figure shows the 10 min time step signal for the reference and shallowing state, and the corresponding moving averages calculated over two tides (24.8 hs).

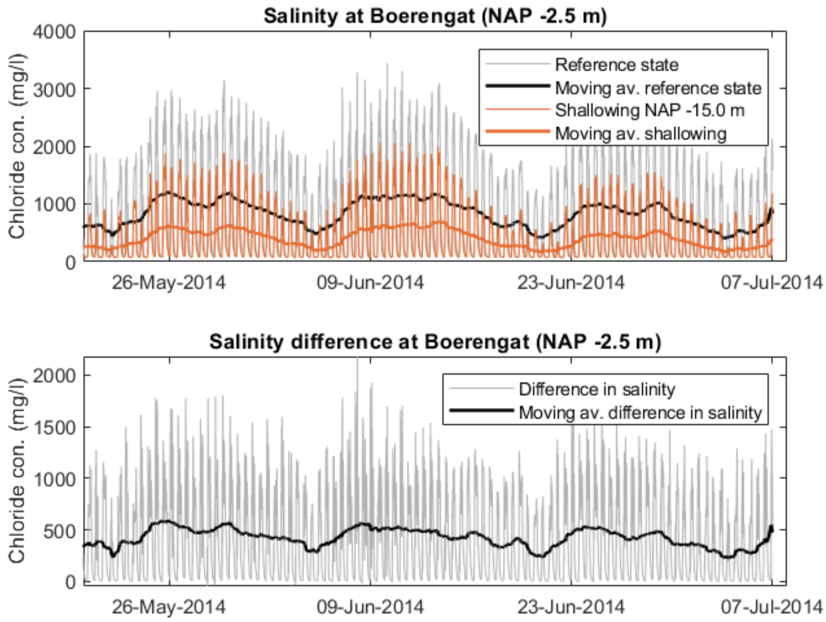


Figure B.23: Impact of shallowing NAP -13.5 m on chloride concentration at Boerengat. Values are computed at a water depth of approximately NAP -2.5 m, since this is the water inlet suction depth. The figure shows the 10 min time step signal for the reference and shallowing state, and the corresponding moving averages calculated over two tides (24.8 hs).

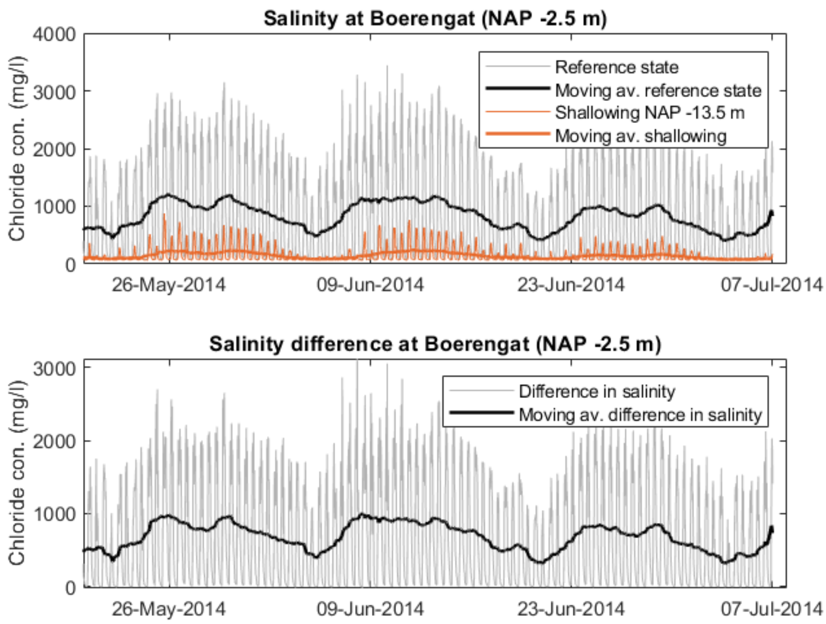


Figure B.24: Impact of shallowing NAP -12.5 m on chloride concentration at Boerengat. Values are computed at a water depth of approximately NAP -2.5 m, since this is the water inlet suction depth. The figure shows the 10 min time step signal for the reference and shallowing state, and the corresponding moving averages calculated over two tides (24.8 hs).

B.1.4. Additional simulations for a scenario with wind set-up

Three additional simulations were conducted for a scenario with low river discharge and wind set-up (Salinisation Type 1 according to [de Vries, 2014]). These simulations correspond to the reference and two shallowing states (+ 1.9 m and + 3.9 m). Results were obtained for the two study locations on the Nieuwe Maas, Boerengat and Brienenoord (see Figure B.26). At least two large storm peaks are identified in the simulation period (set-up > 1 m), each one with a duration of around one tidal period. In each case, the entire storm event lasts between 1-2 days.

In a large salinisation event on the 13-01-2017, the chloride content peak is 5700 mg/l for the reference case. For a bed level increase of + 1.9 m, this peak reduces to 4650 mg/l (reduction of 18 %). For a bed level increase of + 3.9 m, it reduces even further to 4100 mg/l (reduction of 28 %). A second large salinisation event occurs on the 13th and 14th, with a similar reduction due to shallowing. In all cases, chloride content is far over the legal standards of 400 mg/l and 150 mg/l for agricultural and drinking use, respectively.

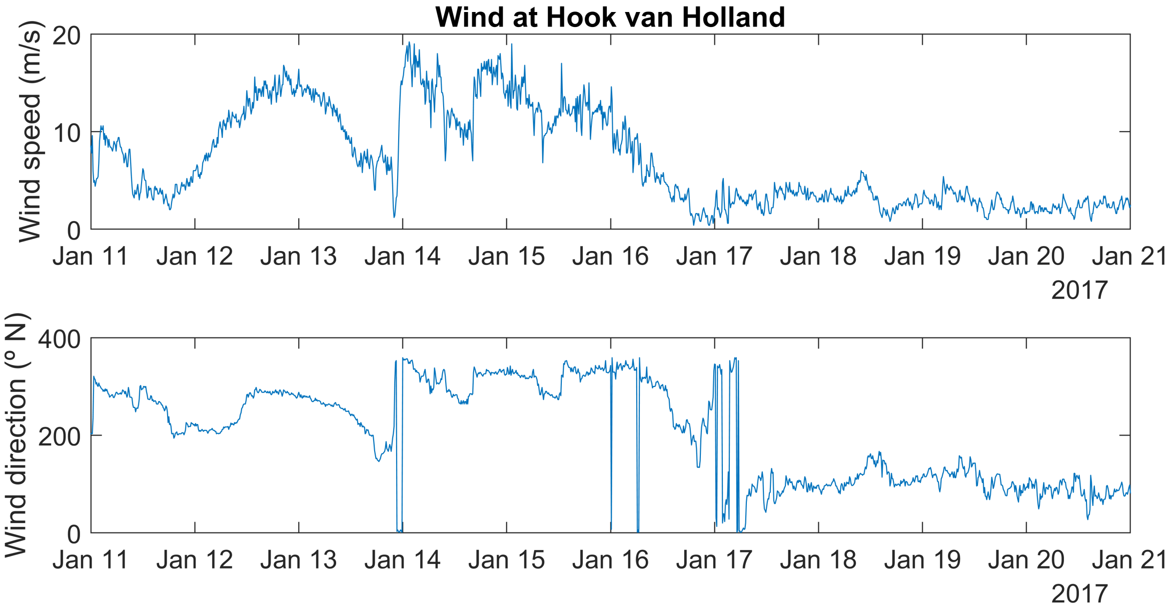


Figure B.25: Wind forcing used in the OSR-model for the simulations described in Section B.1.4. The upper plot shows the wind direction, and the lower plot presents the wind speed. As seen from the figure, high wind speeds over 10 m/s are present between the 12th and 16th of January.

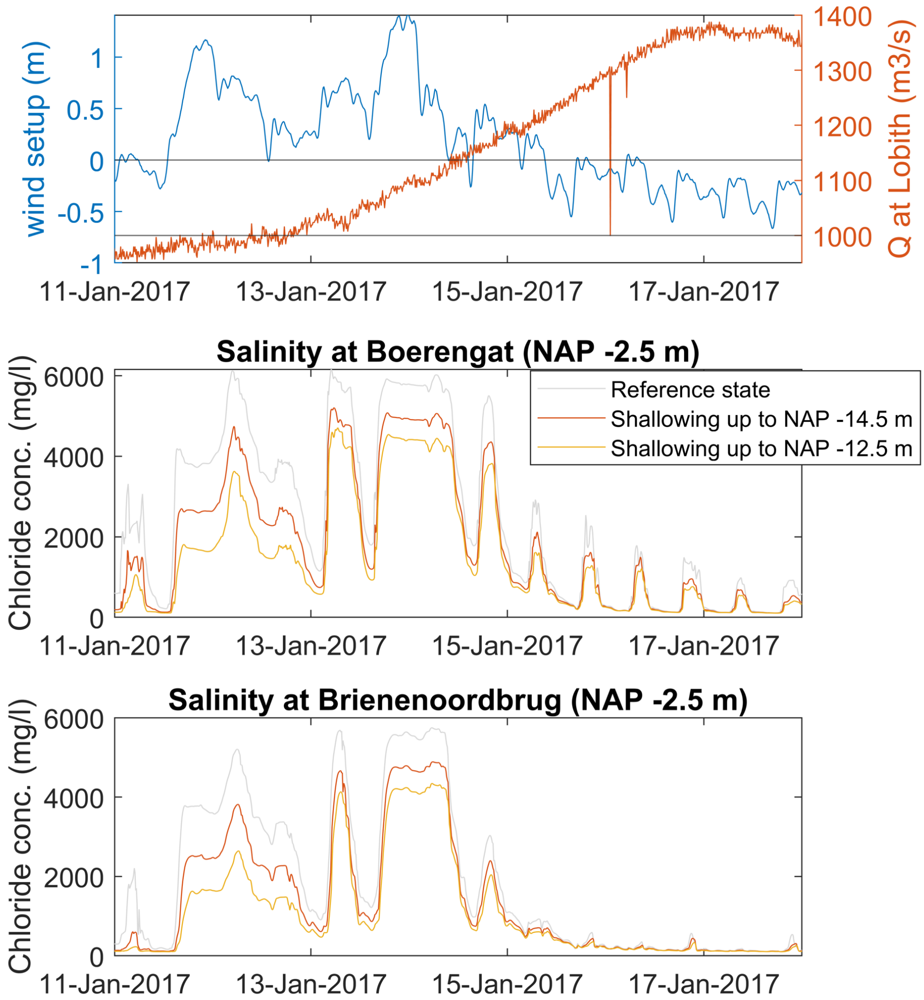


Figure B.26: Salinisation event during a period with low river discharge and low storms in the year 2017. The top figure shows the river discharge measured at Lobith and the wind-set up at Hoek van Holland. Here, wind set-up was estimated by subtracting the astronomical tide from the measured water level. The middle and bottom figures show the chloride content time series at Boerengat and Brienenoordbrug, as calculated with the OSR model. As it can be seen from the maximum values of wind-set up, two storm events occurred between the 12th and 16th of January, which led to large salinity peaks with chloride concentrations over 2000 mg/l.

C

Numerical modelling study - Port traffic

This chapter is divided in two section. First, Section C.1 provides additional information about the OpenTNSim model set-up. Secondly, Section C.2 presents additional model results.

C.1. OpenTNSim model set-up

This section describes the different parts of the modelling study with OpenTNSim, in such a way it can be reproduced by the reader. The following sections are structured according to the stages followed in the main text (see Step 3 (second part) in Chapter 3):

1. Traffic network and bathymetry.
2. Vessels nautical behaviour.
3. Fleet composition (vessel properties).
4. Arrival process and throughput calculation.
5. Tidal windows calculation.

1- Traffic network properties

The total distance from origin to destination is 122 Km, from which only 27 km are covered in the final part between the estuary mouth and the terminal. Along this stretch of route, the nodes of the network are defined according to changes in bed level defined by the stair-steps configuration. The first 95 km of the route are voyaged by the ship through the North Sea. This outermost starting point is located near two anchorage areas used by the Port of Rotterdam for these type of vessels. These are named '3A' and '3C' according to the port chart(hrefportofrotterdam.maps.arcgis.comHavenkaart).

Besides, special nodes are:

- Node 14 (Scheurkade): Controlling point for tidal windows according to the Port of Rotterdam Policy.
- Node 15: Controlling point used in this modelling study to compute the horizontal tidal window.

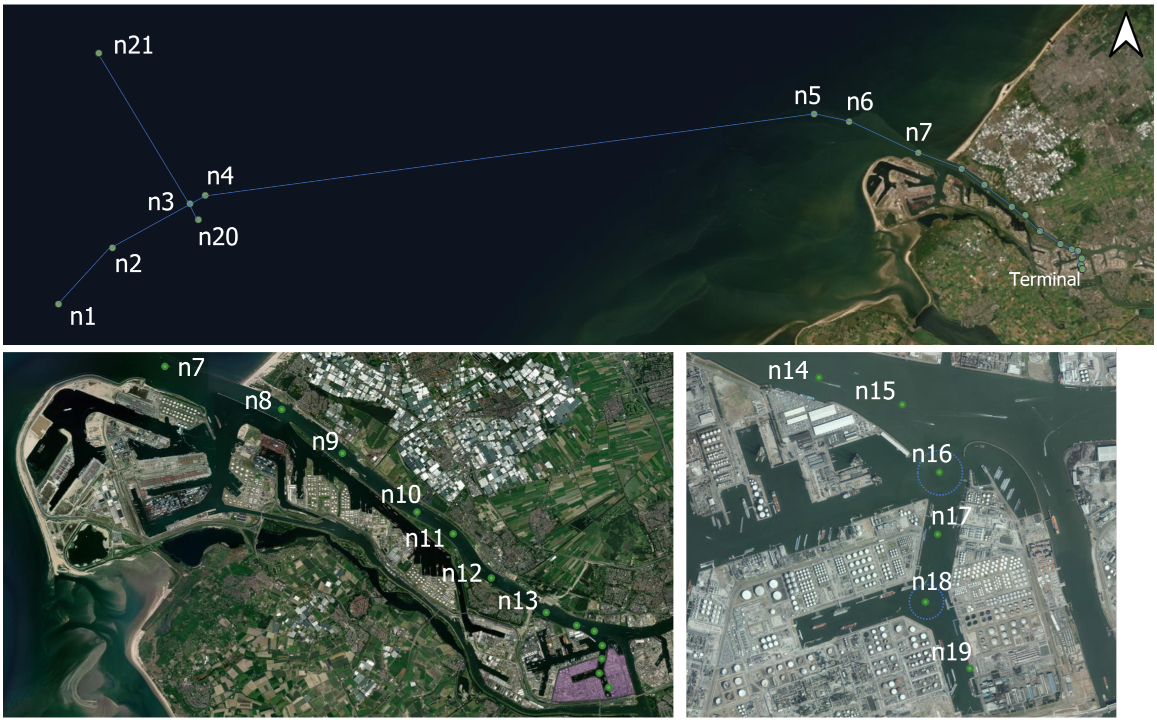


Figure C.1: Traffic network in the OpenTNSim model.

Table C.1: Traffic network properties.

Edge	lon. node 1	lat node 1	lon node 2	lat node 2	MBL (NAP m)[1]	Description
n1 to n2	2.68276	51.84278	2.76847	51.89810	-50.0	Outer channel
n2 to n3	2.76847	51.89810	2.89251	51.94136	-50.0	Outer channel
n3 to n4	2.89251	51.94136	2.91627	51.94957	-50.0	Outer channel
n4 to n5	2.91627	51.94957	3.88419	52.02922	-50.0	Outer channel
n5 to n6	3.88419	52.02922	3.93996	52.02192	-50.0	Outer channel
n6 to n7	3.93996	52.02192	4.04962	51.99131	-24.3	Outer channel
n7 to n8	4.04962	51.99131	4.11878	51.97563	-16.2	Outer channel
n8 to n9	4.11878	51.97563	4.15472	51.95963	-16.2	N. Waterweg
n9 to n10	4.15472	51.95963	4.19884	51.93823	-16.2	N. Waterweg
n10 to 11	4.19884	51.93823	4.22031	51.93029	-16.2	N. Waterweg
n11 to n12	4.22031	51.93029	4.24287	51.91419	-16.4	N. Waterweg
n12 to n13	4.24287	51.91419	4.27537	51.90158	-16.4	N. Waterweg
n13 to n14	4.27537	51.90158	4.29338	51.89689	-16.4	N. Waterweg
n14 to n15	4.29338	51.89689	4.30389	51.89478	-16.4	N. Waterweg
n15 to n16	4.30389	51.89478	4.30856	51.88952	-15.9	Entrance 3e PH
n16 to n17	4.30856	51.88952	4.30834	51.88469	-15.9	3e PH turning basin
n17 to n18	4.30834	51.88469	4.30680	51.87943	-15.9	3e PH turning basin
n18 to n19	4.30680	51.87943	4.31239	51.87426	-15.9	To Koole terminal
n3 to n20	2.89251	51.94136	2.90540	51.92534	-50.0	To anchorage 3C
n3 to n21	2.89251	51.94136	2.74740	52.08876	-50.0	To anchorage 3A

[1] Maintained Bed Level for the reference case.

Bathymetry

The bathymetry is schematized as a one-dimensional profile along the edges of the network. For each node, a value of the MBL is defined (Table C.2).

Table C.2: Maintained Bed Level of the nautical infrastructure for all modelled states.

Edge	Reference	Shall. 1	Shall. 2	Shall. 3	Shall. 4	Shall. 5	Shall. 6
node_1 to node_2	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0
node_2 to node_3	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0
node_3 to node_4	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0
node_4 to node_5	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0
node_5 to node_6	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0
node_6 to node_7	**-24.3**	**-24.3**	**-24.3**	**-24.3**	**-24.3**	**-24.3**	**-24.3**
node_ to node_8	**-16.2**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_8 to node_9	**-16.2**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_9 to node_10	**-16.2**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_10 to node_11	**-16.2**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_11 to node_12	**-16.4**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_12 to node_13	**-16.4**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_13 to node_14	**-16.4**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_14 to node_15	**-16.4**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_15 to node_16	**-15.9**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_16 to node_17	**-15.9**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_17 to node_18	**-15.9**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_18 to node_9	**-15.9**	**-15.0**	**-14.5**	**-13.5**	**-13.1**	**-12.8**	**-12.5**
node_3 to node_20	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0
node_3 to node_21	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0

3- Vessel classes properties

Table C.3: Vessels properties for the 8 vessel classes considered for the logistic modelling study. Dimensions are based on United States. Bureau of Transportation Statistics [2020]. Dead weight Tonnage (DWT) values are based on real tanker vessels calling at the Port of Rotterdam, for the same length and width according to www.marinetraffic.com. The required water depth is computed according to equations presented in Section 2.7 using Freshwater Allowance and Underkeel Clearance policies of the Port of Rotterdam (see also Appendix A). Mean service times are assumed to be equal to the values used in the EIA for the deepening of the Nieuwe Waterweg [Arcadis, 2015].

Vessel class	**L (m)**	**B (m)**	**D (m)**	**DWT (ton)**	**Required water depth (m)**	Mean service time (hs)
Small coaster 1	71	10.1	4.50	1,516	5.00 - 5.06	15.0
Small coaster 2	110	13.5	5.45	4,400	6.05 - 6.13	16.7
Coaster	126	19	8.50	11,340	9.44 - 9.56	16.7
Handy Size Tanker	149	22	10.00	18,684	11.10 - 11.25	18.3
Medium Range Tanker	184	27	11.40	37,596	12.65 - 12.83	18.3
Long Range 1 Tanker	228	32	12.10	74,986	13.43 - 13.61	18.3
Long Range 2 Tanker (partially-loaded)	243	42	13.6	104,955	15.10 - 15.30	18.3
Long Range 2 Tanker	249	42	15.00	122,018	16.65 - 16.88	18.3

4- Arrival process and throughput calculation for each simulation

Table C.4: Calculation of the Inter-arrival time and terminal throughput for the Reference state.[a]

–	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Throughput (Mm3)	11.853	12.581	12.585	14.435	12.690	12.763
Seed	1	2	3	4	5	6
Inter-arrival time (hs)	10	10	10	10	10	10
–	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Throughput (m3)	13.236	12.089	13.897	11.428	11.750	13.941
Seed	7	8	9	10	11	12
Inter-arrival time (hs)	10	10	10	10	10	10
–	Run 13	Run 14	Run 15	–	–	–
Throughput (m3)	12.136	11.257	14.129	–	–	–
Seed	13	14	15	–	–	–
Inter-arrival time (hs)	10	10	10	–	–	–

reference state: 12,756,253 m3; fleet composition: 8 vessel classes

[a] Mean throughput

Table C.5: Calculation of the Inter-arrival time and terminal throughput for the Shallowing 1 state.[a]

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Throughput (m3)	11.805	12.674	12.609	14.364	12.677	12.809
Seed	1	2	3	4	5	6
Inter-arrival time (hs)	8.8	9	8.8	9.35	8.75	9.1
-	Run 7	Run 8	Run 9	Run 10	–	–
Throughput (m3)	13.211	12.095	13.932	11.424	–	–
Seed	7	8	9	10	–	–
Inter-arrival time (hs)	9	10	8.95	9.4	–	–

Shall. 1: 12,760,395 m3; fleet composition: 7 vessel classes

[a] Mean throughput

Table C.6: Calculation of the Inter-arrival time and terminal throughput for the Shallowing 2 state.[a]

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Throughput (m3)	11.838	12.553	12.558	14.383	12.673	12.744
Seed	1	2	3	4	5	6
Inter-arrival time (hs)	8.05	8.4	8.3	8.35	8.05	8.25
-	Run 7	Run 8	Run 9	Run 10	–	–
Throughput (m3)	13.181	12.068	13.848	11.468	–	–
Seed	7	8	9	10	–	–
Inter-arrival time (hs)	8.4	8.9	8.15	8.6	–	–

Shall. 2: 12,731,992 m3; fleet composition: 6 vessel classes

[a] Mean throughput

Table C.7: Calculation of the Inter-arrival time and terminal throughput for the Shallowing 3 and 4 states.[a]

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Throughput (m3)	11.838	12.553	12.558	14.383	12.673	12.744
Seed	1	2	3	4	5	6
Inter-arrival time (hs)	8.05	8.4	8.3	8.35	8.05	8.25
-	Run 7	Run 8	Run 9	Run 10	–	–
Throughput (m3)	13.181	12.068	13.848	11.468	–	–
Seed	7	8	9	10	–	–
Inter-arrival time (hs)	8.4	8.9	8.15	8.6	–	–

Shall. 3 and 4: 12,731,992 m3; fleet composition: 6 vessel classes

[a] Mean throughput

Table C.8: Calculation of the Inter-arrival time and terminal throughput for the Shallowing 5 and 6 states.[a]

–	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Throughput (m3)	11.836	12.492	12.362	14.311	12.654	12.735
Seed	1	2	3	4	5	6
Inter-arrival time (hs)	5.4	5.6	5.6	5.35	5.55	5.7
–	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Throughput (m3)	13.213	12.109	13.952	11.353	11.752	13.823
Seed	7	8	9	10	11	12
Inter-arrival time (hs)	5.5	6	5.3	5.85	5.9	5.45
–	Run 13	Run 14	Run 15	–	–	–
Throughput (m3)	12.177	11.311	13.928	–	–	–
Seed	13	14	15	–	–	–
Inter-arrival time (hs)	5.6	6	5.25	–	–	–

Shall. 5 and 6: 12,702,141 m3; fleet composition: 5 vessel classes

[a] Mean throughput

5- Tidal window calculation

This subsection presents an exemplar illustration of the combined tidal window calculation in OpenTNSim. Next, the hydrodynamic time series are presented.

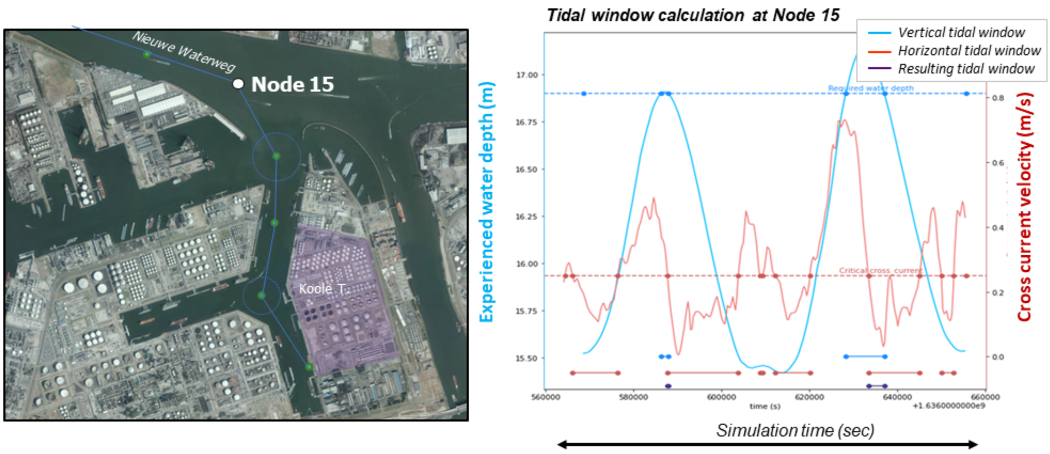


Figure C.2: Tidal window calculation. The right figure details the model network at the 3rd Petroleumhaven basin and Koole terminal. The left figure presents combined tidal window at node 15 as calculated by the model. The available tidal window results from overlapping the vertical and horizontal tidal windows.

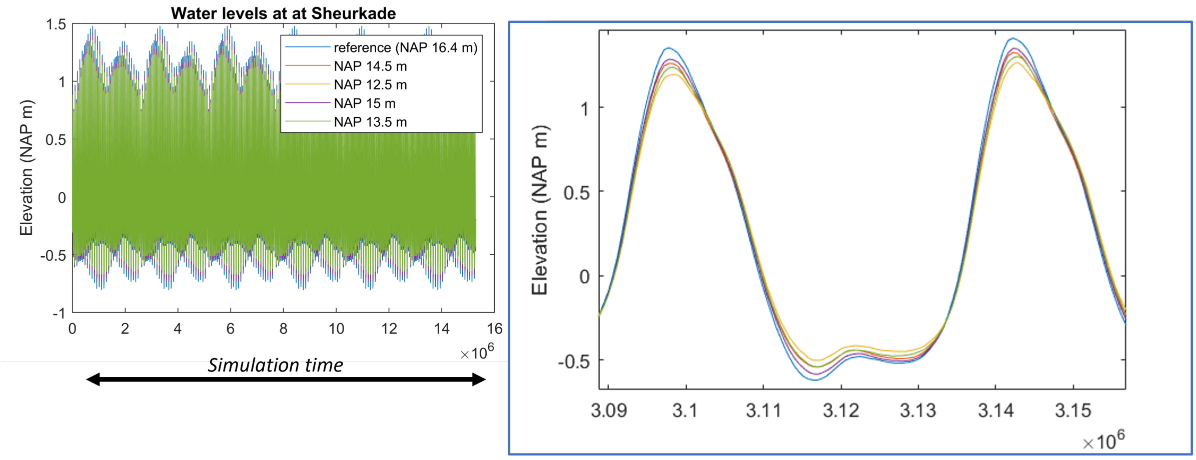


Figure C.3: Left: Water level time series used in the OpenTNSim model. The hydrodynamic conditions for each state (reference and shallowing) were obtained from the OSR model. Right: Extension over slightly more than one tidal period. In this figure, a slight decrease in the tidal range is visible.

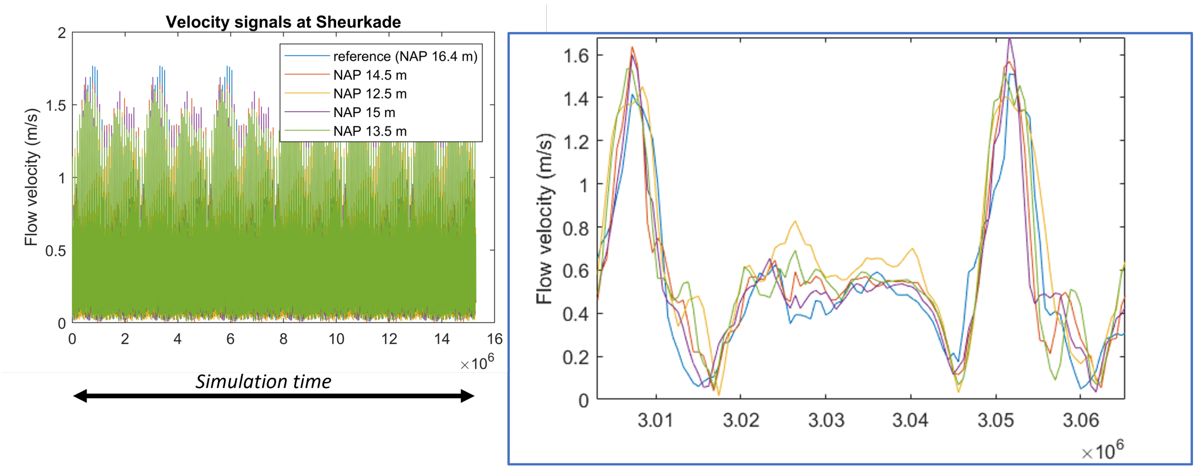


Figure C.4: Left: Velocity magnitude time series used in the OpenTNSim model. The hydrodynamic conditions for each state (reference and shallowing) were obtained from the OSR model. Right: Extension over slightly more than one tidal period. In this figure, a slight increase in flow velocity magnitude is not completely visible. To have better insights on the effect of shallowing on velocity magnitudes, the reader is referred to Figure B.7.

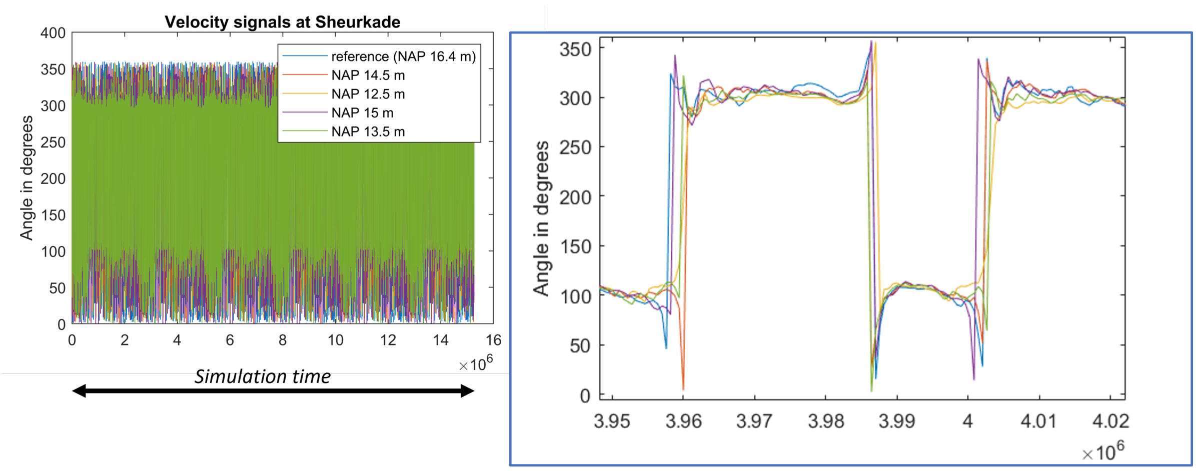


Figure C.5: Left: Velocity angle time series used in the OpenTNSim model. The hydrodynamic conditions for each state (reference and shallowing) were obtained from the OSR model. Right: Extension over slightly more than one tidal period. Non systematic difference can be observed when comparing different shallowing levels.

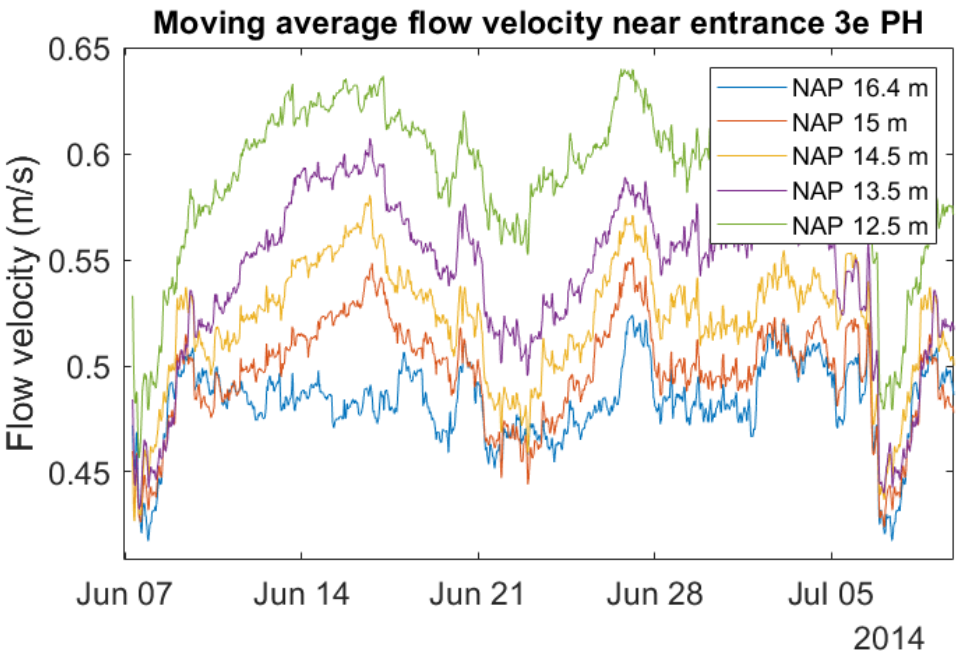


Figure C.6: Moving average of flow velocities calculated over two tidal periods (24.8 hs). The figure presents outcomes for all levels of shallowing, computed at the entrance of the 3e Petroleumhaven (Node 15 in the network).

C.2. OpenTNSim model results

This section describes additional results from the OpenTNSim model.

C.2.1. Traffic simulations

Reference state

Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: LR2, LR2 partially loaded, LR1, Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.9: OpenTNSim model results for the set of runs corresponding to the reference state.

–	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.996	0.995	0.996	0.995	0.996	0.996
Average waiting time (seg)	1129.5	1101.5	1041.6	1192.2	1217.5	892.8
Average turnaround time (seg)	124974	125196	125281	126053	125085	125407
total # of vessels served	391	391	391	391	390	391
Number of encounters	654	658	652	644	651	634
T. occupancy	0.375	0.376	0.377	0.380	0.376	0.379
–	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Berth productivity	0.998	0.996	0.997	0.996	0.997	0.995
Average waiting time (seg)	680.9	1114.3	964.1	1012.3	765.2	1098.2
Average turnaround time (seg)	124967	125595	125273	125022	124462	125444
total # of vessels served	391	391	391	391	391	391
Number of encounters	633	630	639	650	662	645
T. occupancy	0.378	0.379	0.378	0.376	0.374	0.378
–	Run 13	Run 14	Run 15	–	–	–
Berth productivity	0.997	0.997	0.995	–	–	–
Average waiting time (seg)	810.1	799.3	1295.0	–	–	–
Average turnaround time (seg)	124634	124817	125905	–	–	–
total # of vessels served	391	391	391	–	–	–
Number of encounters	662	640	647	–	–	–
T. occupancy	0.375	0.376	0.379	–	–	–

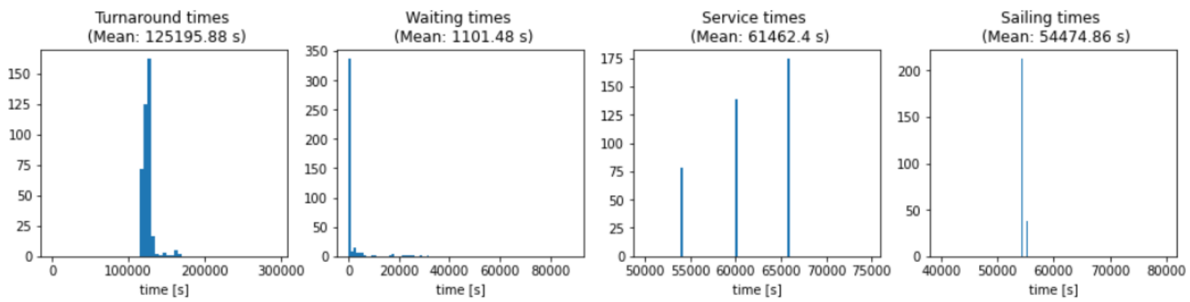


Figure C.7: OpenTNSim model results for the reference state. Waiting times, turnaround times and service times distributions for Run 1.

Shallowing 1 state - bed level change +1.4 m (NAP -15.0 m)

Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: LR2 partially loaded, LR1, Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.10: OpenTNSim model results for the set of runs corresponding to the Shallowing 1 state.

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.997	0.996	0.997	0.996	0.995	0.998
Average waiting time (seg)	581.5	649.1	721.0	754.6	724.8	496.6
Average turnaround time (seg)	124199	124760	124793	124859	124588	124641
total # of vessels served	447	437	447	420	450	432
Number of encounters	765	610	773	592	789	571
T. occupancy	0.431	0.424	0.433	0.408	0.434	0.419
-	Run 7	Run 8	Run 9	Run 10	–	–
Berth productivity	0.997	0.995	0.996	0.995	–	–
Average waiting time (seg)	839.6	757.7	679.8	770.2	–	–
Average turnaround time (seg)	125194	125186	124934	124722	–	–
total # of vessels served	437	391	440	417	–	–
Number of encounters	581	634	610	702	–	–
T. occupancy	0.426	0.383	0.427	0.405	–	–

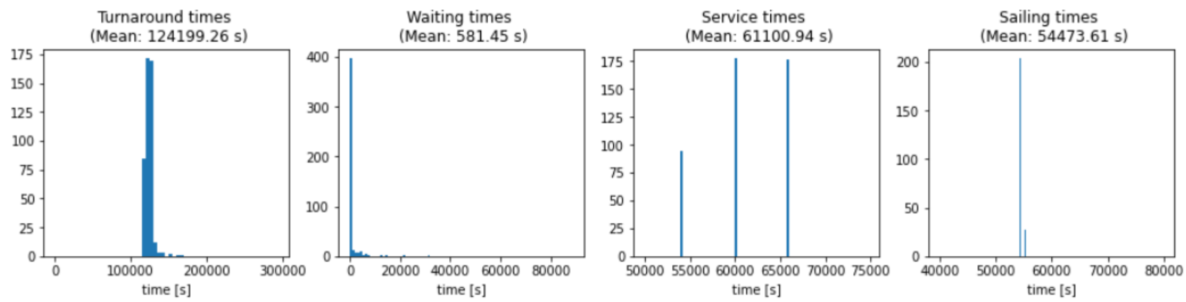


Figure C.8: OpenTNSim model results for the shallowing 1 state. Waiting times, turnaround times and service times distributions for Run 1.

Shallowing 2 state - bed level change +1.9 m (NAP -14.5 m) Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: LR1, Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.11: OpenTNSim model results for the set of runs corresponding to the Shallowing 2 state.

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.999	1.000	0.998	0.999	0.999	0.999
Average waiting time (seg)	512.0	558.8	583.0	468.7	467.3	736.4
Average turnaround time (seg)	123817	124316	124395	124727	123968	124695
total # of vessels served	491	470	476	473	491	479
Number of encounters	1025	908	898	924	1026	913
T. occupancy	0.469	0.452	0.457	0.457	0.470	0.461
-	Run 7	Run 8	Run 9	Run 10	–	–
Berth productivity	0.999	0.998	0.999	0.999	–	–
Average waiting time (seg)	580.3	728.5	660.8	487.8	–	–
Average turnaround time (seg)	124630	124792	124630	124191	–	–
total # of vessels served	470	442	485	458	–	–
Number of encounters	941	601	924	781	–	–
T. occupancy	0.454	0.428	0.467	0.441	–	–

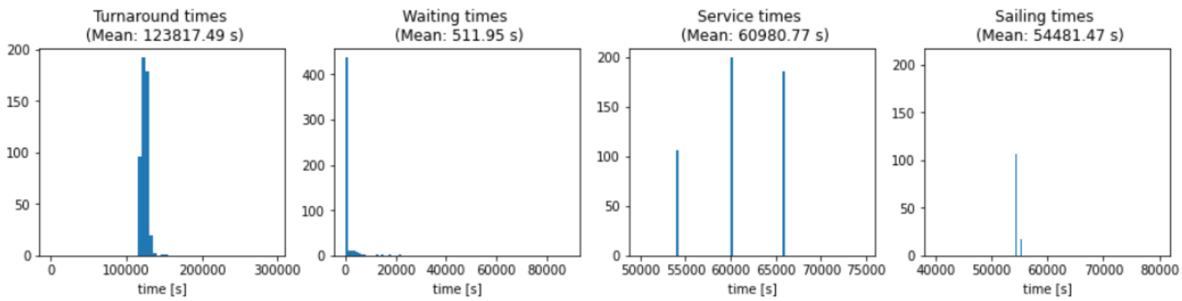


Figure C.9: OpenTNSim model results for the shallowing 2 state. Waiting times, turnaround times and service times distributions for Run 1.

Shallowing 3 state - bed level change +2.9 m (NAP -13.5 m)

Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: LR1, Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.12: OpenTNSim model results for the set of runs corresponding to the Shallowing 3 state.

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.983	0.979	0.979	0.976	0.979	0.982
Average waiting time (seg)	1701.6	2070.3	2862.6	2363.8	1929.9	1961.3
Average turnaround time (seg)	126366	127490	128322	128554	127057	127310
total # of vessels served	491	470	475	472	491	479
Number of encounters	1023	913	916	931	1026	898
T. occupancy	0.478	0.462	0.468	0.469	0.480	0.470
-	Run 7	Run 8	Run 9	Run 10	–	–
Berth productivity	0.979	0.980	0.976	0.983	–	–
Average waiting time (seg)	2161.3	2365.2	2546.0	1558.8	–	–
Average turnaround time (seg)	127797	127894	128363	126525	–	–
total # of vessels served	469	442	485	458	–	–
Number of encounters	948	645	919	771	–	–
T. occupancy	0.465	0.437	0.478	0.449	–	–

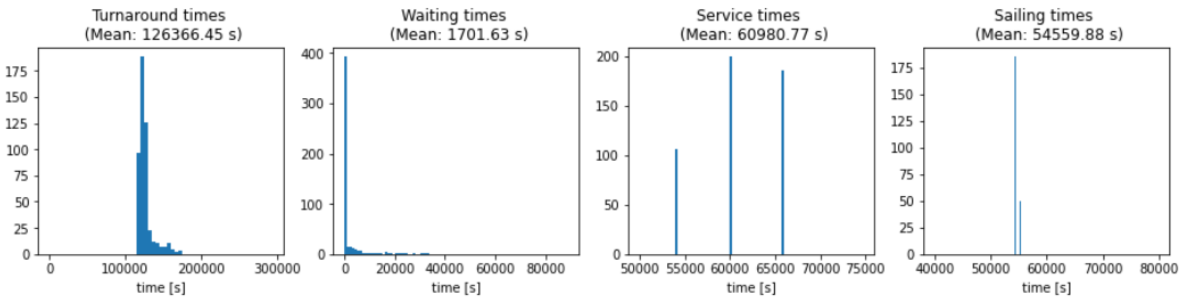


Figure C.10: OpenTNSim model results for the shallowing 3 state. Waiting times, turnaround times and service times distributions for Run 1.

Shallowing 4 state - bed level change +3.3 m (NAP -13.1 m)

Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: LR1, Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.13: OpenTNSim model results for the set of runs corresponding to the Shallowing 4 state.

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.971	0.967	0.966	0.958	0.967	0.966
Average waiting time (seg)	3075.8	2925.5	3677.3	3600.1	3298.2	3302.3
Average turnaround time (seg)	128726	129387	130246	131268	129547	129993
total # of vessels served	491	470	475	472	491	479
Number of encounters	1044	902	925	921	1044	910
T. occupancy	0.484	0.469	0.475	0.478	0.488	0.479

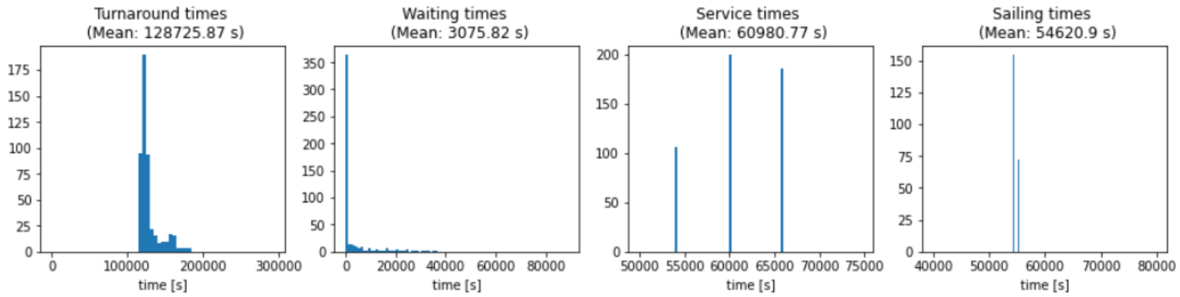


Figure C.11: OpenTNSim model results for the shallowing 4 state. Waiting times, turnaround times and service times distributions for Run 1.

Shallowing 5 state - bed level change +3.6 m (NAP -12.8 m)

Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.14: OpenTNSim model results for the set of runs corresponding to the Shallowing 5 state.

-	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.984	0.981	0.980	0.976	0.981	0.981
Average waiting time (seg)	12386.8	8485.7	10183.6	117980.0	11208.2	8319.7
Average turnaround time (seg)	137027	133608	135277	244243	136469	133592
total # of vessels served	745	717	717	741	722	703
Number of encounters	2408	2221	2242	2483	2237	2049
T. occupancy	0.706	0.686	0.686	0.714	0.691	0.674
-	Run 7	Run 8	Run 9	Run 10	–	–
Berth productivity	0.980	0.983	0.978	0.985	0.982	–
Average waiting time (seg)	15475.3	4639.9	149415.0	5019.6	5055.8	–
Average turnaround time (seg)	141104	129649	275258	129659	129958	–
total # of vessels served	728	668	745	686	678	–
Number of encounters	2370	1680	2496	1884	1855	–
T. occupancy	0.703	0.642	0.716	0.654	0.651	–

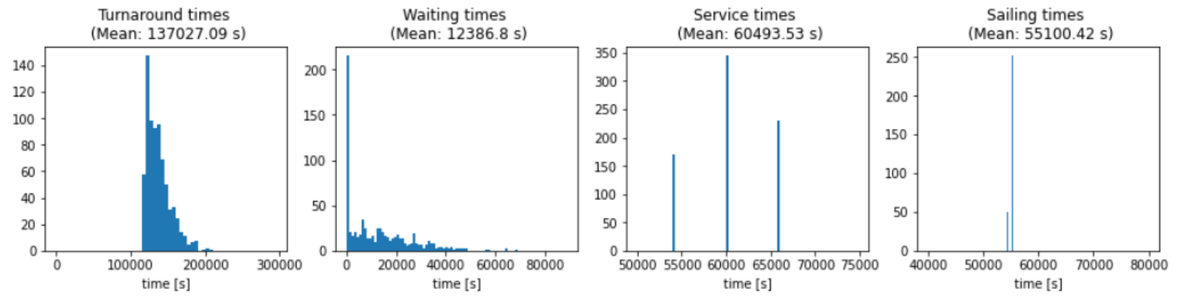


Figure C.12: OpenTNSim model results for the shallowing 5 state. Waiting times, turnaround times and service times distributions for Run 1.

Shallowing 6 state - bed level change +3.9 m (NAP -12.5 m)

Simulation duration: 15,084,000 sec
Spin-up time: 500,000 sec
Fleet composition: Medium Range, Handysize, Coaster, Small Coaster 1, Small Coaster 2.

Table C.15: OpenTNSim model results for the set of runs corresponding to the Shallowing 6.

–	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Berth productivity	0.979	0.978	0.976	0.973	0.977	0.977
Average waiting time (seg)	16779.5	10426.8	11312.2	132901.5	13481.9	8776.7
Average turnaround time (seg)	141866	135886	136778	259474	139084	134386
total # of vessels served	745	717	717	740	722	703
Number of encounters	2427	2248	2264	2545	2288	2050
T. occupancy	0.710	0.690	0.689	0.717	0.695	0.677
–	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Berth productivity	0.974	0.979	0.972	0.982	0.978	0.972
Average waiting time (seg)	18024.0	5462.8	191823.7	5529.8	5453.7	50288.9
Average turnaround time (seg)	144216	130854	318134	130488	130656	176682
total # of vessels served	729	668	739	686	678	736
Number of encounters	2410	1694	2569	1897	1866	2504
T. occupancy	0.708	0.645	0.717	0.657	0.654	0.714
–	Run 13	Run 14	Run 15	–	–	–
Berth productivity	0.979	0.982	0.974	–	–	–
Average waiting time (seg)	9217.1	3955.5	258179.5	–	–	–
Average turnaround time (seg)	134471	128763	384600	–	–	–
total # of vessels served	717	667	744	–	–	–
Number of encounters	2238	1704	2574	–	–	–
T. occupancy	0.687	0.641	0.721	–	–	–

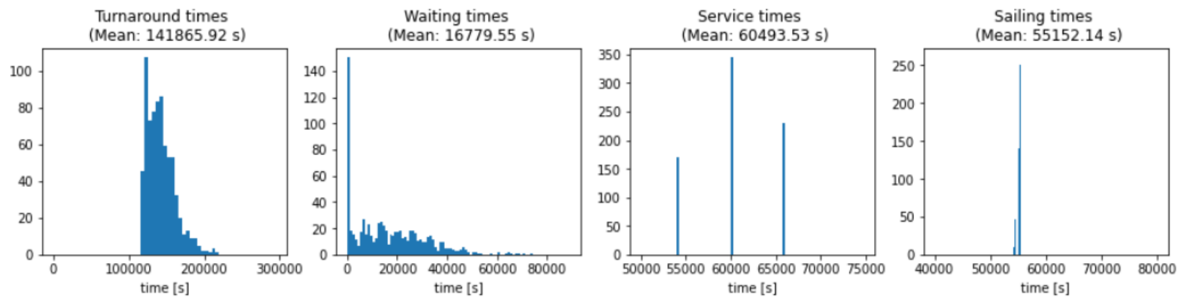


Figure C.13: OpenTNSim model results for the shallowing 6 state. Waiting times, turnaround times and service times distributions for Run 1.

D
Fitting models

Data fitting was done with the Curve Fitting Toolbox developed by MatLab, a numerical computing environment and proprietary programming language developed by MathWorks [MATLAB, 2020].

D.0.1. Boerengat - Drinking water use (threshold 150 mg/l)

Linear model Polynomial degree 2:
Robust: LAR

$$f(x) = p1 * x^2 + p2 * x + p3 \tag{D.1}$$

Coefficients (with 95% confidence bounds):
p1 = -0.6115 (-0.8912, -0.3318)
p2 = -4.474 (-5.624, -3.324)
p3 = 28.42 (27.38, 29.45)

Goodness of fit:
SSE: 0.1208
R-square: 0.9997
Adjusted R-square: 0.9994
RMSE: 0.2458

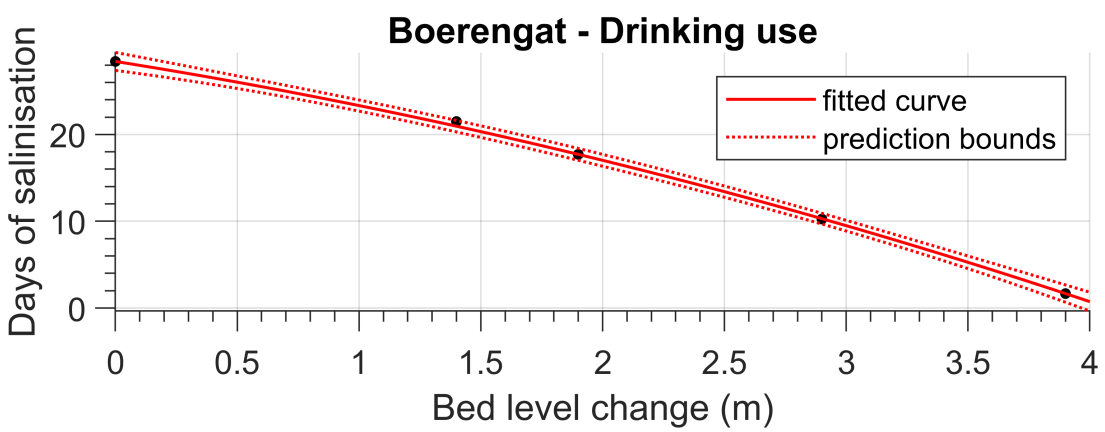


Figure D.1: Prediction of confidence bounds for the fitting function corresponding to drinking water use at Boerengat. The data points in the figure were obtained after processing results from the salt transport NSC-OSR model.

D.0.2. Boerengat - Agricultural water use (threshold 400 mg/l)

Linear model Polynomial degree 3:
Robust: LAR

$$f(x) = p1 * x^3 + p2 * x^2 + p3 * x + p4 \quad (D.2)$$

Coefficients (with 95% confidence bounds):
p1 = 0.6322 (-0.2567, 1.521)
p2 = -3.385 (-8.591, 1.82)
p3 = -2.029 (-9.601, 5.543)
p4 = 21.92 (19.15, 24.69)

Goodness of fit:
SSE: 0.04749
R-square: 0.9998
Adjusted R-square: 0.9994
RMSE: 0.2179

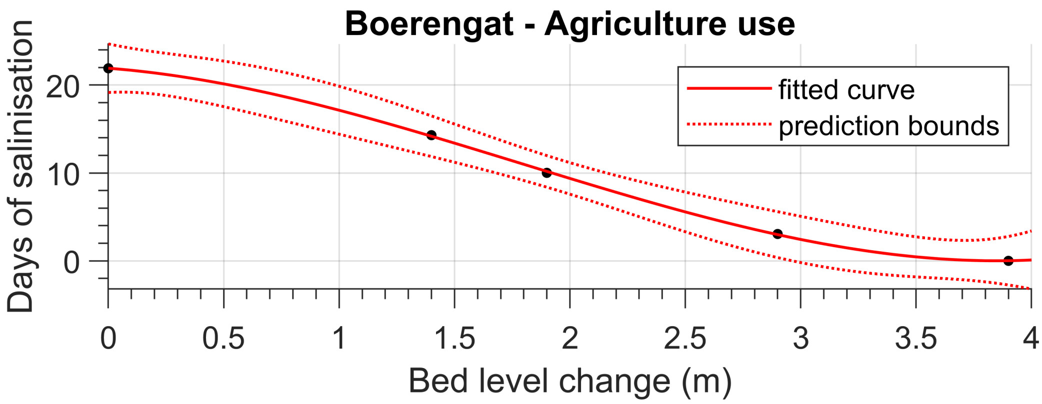


Figure D.2: Prediction of confidence bounds for the fitting function corresponding to agricultural water use at Boerengat. The data points in the figure were obtained after processing results from the salt transport NSC-OSR model.

D.0.3. Brienenoordbrug - Drinking water use (threshold 150 mg/l)

Linear model Polynomial degree 2:
Robust: LAR

$$f(x) = p1 * x^2 + p2 * x + p3 \tag{D.3}$$

Coefficients (with 95% confidence bounds):
p1 = 0.4496 (-1.369, 2.268)
p2 = -6.479 (-13.96, 0.9983)
p3 = 18.43 (11.69, 25.17)

Goodness of fit:
SSE: 5.108
R-square: 0.9775
Adjusted R-square: 0.9549
RMSE: 1.598

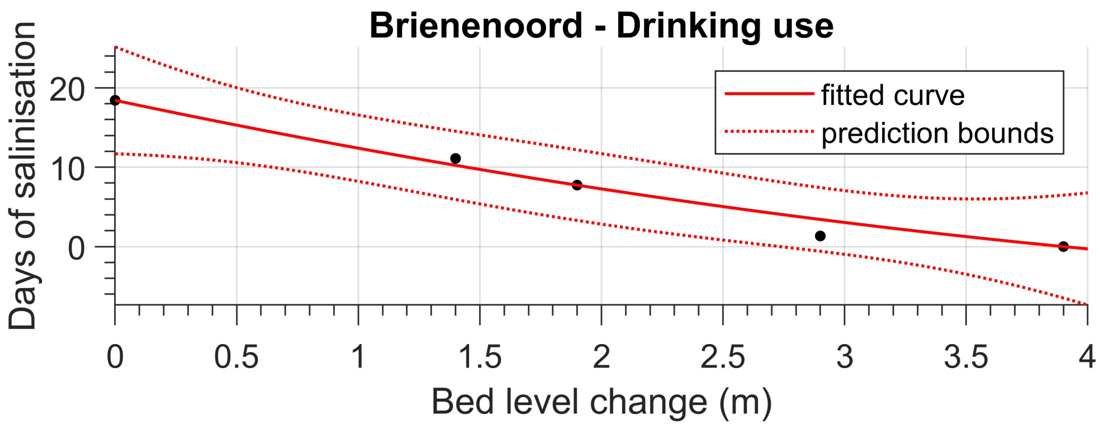


Figure D.3: Prediction of confidence bounds for the fitting function corresponding to drinking water use at Brienenoord. The data points in the figure were obtained after processing results from the salt transport NSC-OSR model.

D.0.4. Brienenoordbrug - Agricultural water use (threshold 400 mg/l)

General model Exponential fit:

$$f(x) = a * exp(b * x) \tag{D.4}$$

Coefficients (with 95% confidence bounds):
a = 11.64 (10.23, 13.05)
b = -1.281 (-1.697, -0.865)

Goodness of fit:
SSE: 0.5892
R-square: 0.994
Adjusted R-square: 0.9921
RMSE: 0.4432

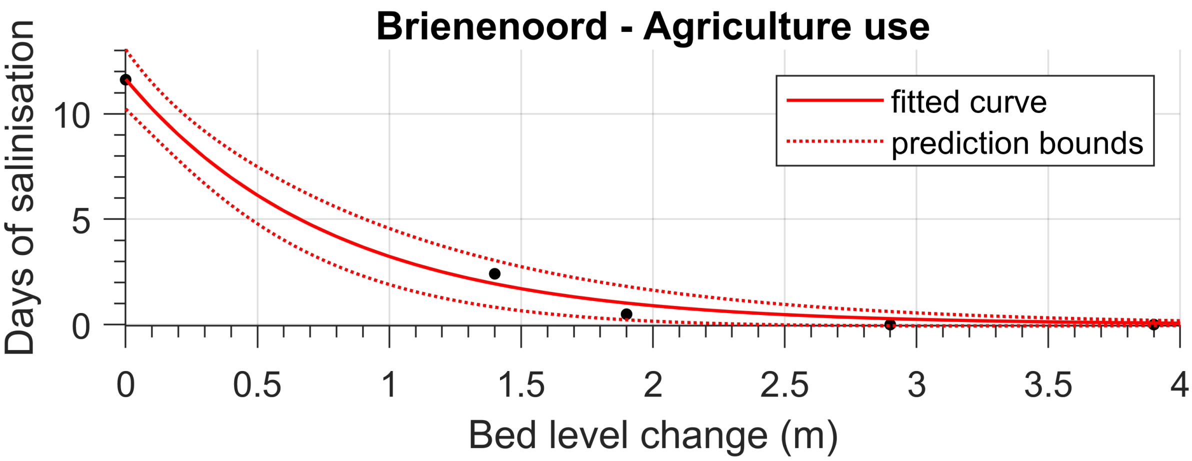


Figure D.4: Prediction of confidence bounds for the fitting function corresponding to agricultural water use at Brienenoord. The data points in the figure were obtained after processing results from the salt transport NSC-OSR model.

D.0.5. Vessel Waiting times

General model exponential fit:

$$f(x) = a * exp(b * x) + c \tag{D.5}$$

Coefficients (with 95% confidence bounds):
a = 4.747e-06 (-4.177e-05, 5.126e-05)
b = 3.824 (1.281, 6.367)
c = 0.1553 (-0.9039, 1.215)

Goodness of fit:
SSE: 0.3938
R-square: 0.9075
Adjusted R-square: 0.8613
RMSE: 0.3138

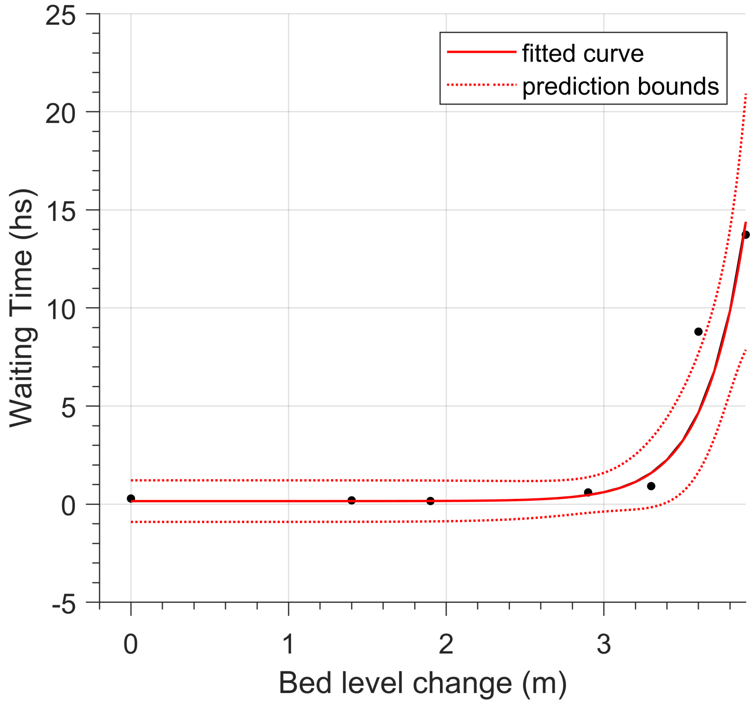


Figure D.5: Prediction of confidence bounds for the fitting function of vessel waiting times. The data points in the figure corresponds to port waiting times computed in the traffic model in OpenTNSim.

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