BSc Thesis Final Report

The Effect of an Underwater Sill against Salt Intrusion on Port Logistics

(by C. Hunter, 2023)

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The Effect of an Underwater Sill against Salt Intrusion on Port Logistics

By

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Preface

This research project was conducted to obtain the bachelor’s degree in civil engineering at the TU Delft faculty of civil engineering and applied earth sciences. The research topic is closely related to current PhD research being conducted by Ir. F. P. Bakker and Ir. G. Hendrickx, and the SALTISolutions WP7.3: *‘’Implications of nature-based SALTISolutions for port logistics’’.*

I would like to thank Floor Bakker for providing thorough guidance during this project. Thanks to you I have learnt significant amounts about port logistics and the complex (hydrodynamic) processes which take place within estuaries. I hope to further develop my interest in ‘’estuarine engineering’’ in the future.

I would also like to thank Gijs Hendrickx for sharing your knowledge regarding underwater sills and saltwater transport. Thank you also for running the DFM simulations, without these this project wouldn’t have been possible.

Lastly I would also like to thank Dr. Poonam Taneja for your enthusiasm regarding the project and your critical second opinion.

Abstract

This research study has investigated the effects of sills as a nature-based countermeasure to reduce saltwater intrusion within Rijnmond Drechtsteden The effects of this measure have been assessed regarding its impact on port logistics and freshwater supply in the region. The heavily dredged New Waterway provides the vital open connection to the sea for port operations. Meanwhile this same waterway allows salt to intrude landwards into the estuary, placing pressure on the freshwater network. With climate change leading to rising sea levels and extreme variations in river discharge, the impacts on both stakeholders are likely to increase. Previous research into bed shallowing indicated detrimental effects for port operations, therefore alternative nature-based solutions need to be investigated such as underwater sills.

The impact of a sill has been assessed using the Frame of Reference approach (Van Koningsveld, 2003). To determine the relationship between each stakeholder, a quantitative trade off has been defined using the comparison tool as per the method of Iglesias (2022). This builds off of the FoR principles. The tool facilitates the comparison of individual effects created by (nature-based) interventions using design parameters and performance indicators.

Via an extensive literature study, critical design parameters were defined for underwater sills. It was concluded that sill height and sill length would have the greatest impact on both the port and the freshwater supply in the region.

Then, the impact on the stakeholders was defined through choosing specific performance indicators and modelling techniques. The performance of port logistics was represented via the percentage of accessible tides and modelled using a simplified case in the nautical traffic model OpenTNSim. The performance of the freshwater supply was quantified using the percentage of freshwater availability, this was modelled using the concept of an idealised estuary in Delft Flexible 3D Mesh (DFM).

The research method takes the operational objective of the port as a base to select specific sill designs. This objective depends on tidally bound inbound vessels having access for 99% of all tides (de Jong, 2020). To comply with this requirement, sill heights of 0.1m, 0.2m, 0.3m and lengths of 2km, 5km, 10km were chosen. The model results show that sill height has a large impact on accessible tides, therefore severely limiting the range of heights that could be considered. Sill length has a lesser impact, allowing for a wider range to be assessed.

The effect of the sill designs on freshwater availability is negligible, with responses varying between 0.01% and 0.8%. This lack of response indicates that the chosen sill designs are too small to have a significant impact on salt intrusion in the channel. The sill designs led to access percentages between 100% and 70%, a wider range of percentages was investigated to see the effect of a more flexible port.

The resulting trade off curves all exhibit linear functions, indicating the lack of any trade off relation between the performance indicators and the sill designs. Since the sill designs fail to achieve both operational objectives, the overall strategic objective is not met. It can therefore be concluded that underwater sills are not feasible in the case study of the Rotterdam waterways.

The research results indicate that other nature-based solutions should be investigated to better suit the actively dredged channels in the Rotterdam waterways. Alternative methods which can synergise with this active dredging characteristic may pose to be significantly effective.

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1. Introduction

1.1 Research Background

In today’s current climate, solutions in hydraulic engineering can no longer afford to serve monofunctional purposes. Present trends such as rising sea levels, ecosystem reduction, the energy transition and rapid urbanisation of delta regions place enormous pressure on engineering infrastructures (de Vriend et al., 2014). In reaction to these developments, the building with nature design philosophy proposes to catalyse natural processes in a multi-functional manner so that stakeholders can benefit sustainably (de Vriend et al., 2014). This approach brings forth various challenges due to the sometimes contradicting interests of stakeholders.

Measures against saltwater intrusion in urban deltas can lead to trade-offs in which stakeholders are inversely affected. For example, the nature-based measure of shallowing improves freshwater availability, yet negatively impact port logistics (Iglesias, 2022). Studies are yet to find (nature-based) measures which sustainably benefit both stakeholders. Initial proof-of-concept research has indicated a clear relation between these effects using the Frame of Reference (FoR) approach developed by Van Koningsveld (2003). The study presents an effective method of analysing impacts on stakeholders which arise from implementing nature-based countermeasures (Iglesias, 2022).

The case study of this research project is Rijnmond-Drechtsteden, which is a region of the wider Rhine-Meuse delta defined by the national delta program. This specific area is characterized by the port of Rotterdam, the delta works and many other stakeholders which are dependent on the dynamics of the system. Examples of these include water safety, ecology and freshwater availability.

The national delta program has created an action plan which aims to protect the freshwater supply in the region till 2050. Figure 1.1 lists the core principles which the plan strives to achieve. Placing a sill would aid this goal by protecting the crucial functions, whilst also maintaining a healthy and balanced water system (Nationaal Delta Programma, n.d.). Furthermore, conducting this research contributes to the development of water knowledge and innovations.

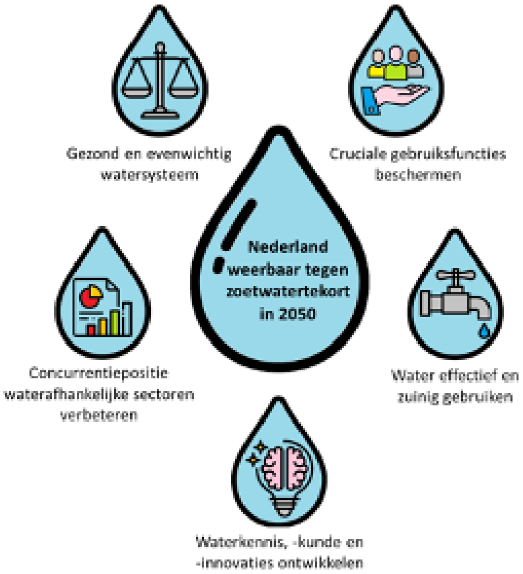

Figure 3.1: *National goals for freshwater supply (Nationaal Deltaprogramma, n.d.)*

1.2 Problem Statement

Further research is required to develop effective nature-based solutions to saltwater intrusion. Bed shallowing is effective at reducing saltwater intrusion, but also leads to unacceptable waiting times for vessels (Iglesias, 2022). Therefore, alternative measures must be investigated which have a lesser impact on the port. This issue is actively being researched under WP7.3 of SALTISolutions: *''Implications of nature-based SALTISolutions for port logistics''* (SALTISolutions, 2019).

Compared to bed shallowing, sills are more spatially concentrated. Instead of raising the riverbed entirely, a specific location is chosen. This is expected to have a less detrimental impact on port performance, but also improve freshwater availability to a lesser extent. As sills are relatively underdeveloped, it is necessary to investigate their exact effects on both stakeholders. This knowledge would help to indicate whether sills can be implemented as an effective nature-based countermeasure to saltwater intrusion.

1.3 Objective and Research Questions:

This research aims to reduce the knowledge gap regarding underwater sills by analysing their effect through the FoR approach. The project utilizes the FoR approach to understand the effectiveness of a sill, namely the implications for the freshwater supply of Rijnmond-Drechtsteden as well as the logistics of the port of Rotterdam. The outcome of this investigation will facilitate an initial assessment, indicating the impact of sills on both stakeholders. These goals are met by answering the following research question:

What is the effectiveness of a sill as a nature-based solution against salt intrusion in Rijnmond Drechtsteden?

To answer the main research question, the following sub-questions have been drafted:

SQ1*:* *How can we apply the FoR approach to a sill?*

SQ2*:* *What methods are required to quantify the trade-off between the performance indicators of the stakeholders?*

SQ3: *What are the effects of an underwater sill on freshwater intake and port logistics, and how do these effects relate?*

1.4 Methodology

The study will follow the methodology of Iglesias (2022) by looking at the relationship between and the effects of a sill on:

- Salt transport and the impact on freshwater intake.
- Port logistics in the Port of Rotterdam.

The research methodology starts by investigating nature-based solutions, the FoA approach, estuarine dynamics, port logistics and sill design. This knowledge will provide insight into the implementation of sills and their critical design parameters regarding the stakeholder context (SQ1). Furthermore, the review shall provide essential knowledge to determine performance indicators which accurately describe the impact on each stakeholder.

Next, the identified principles from the comparison tool as defined by Iglesias (2022) are applied to assess the effects of the design parameter on each performance indicator (SQ2). The effects on saltwater intrusion and freshwater intake will be simulated using the concept of an idealised estuary which resembles the Rhine-Meuse delta. This is done using Delft 3D Flexible Mesh (DFM). The effects on port logistics will be simulated using the nautical traffic model OpenTNSim.

Both computational models can assess the new bed profile due to the placement of a sill. DFM can quantify salt intrusion (and freshwater intake), while OpenTNSim can estimate the effects on the performance of the port. For this, OpenTNSim utilises water level data from the DFM simulations. Further simulations may be required depending on the obtained results.

Using the obtained simulation results, a quantitative trade off can be defined according to the method of Iglesias (2022). This will indicate the relation between the effects of an underwater sill on both stakeholders (SQ3).

1.5 Report Structure

The study is structured into six chapters. **Chapter 2** contains the literature review on relevant topics and theory. **Chapter 3** describes the utilised research method. **Chapter 4** showcases the obtained results from the models, and their relation in the form of a quantitative trade-off. **Chapter 5** presents the discussion of the obtained results. **Chapter 6** presents the final conclusions and further recommendations of the research.

2. Literature Review

This chapter lists the important findings from the literature review. Sections 2.1 - 2.3 present relevant concepts including the comparison tool, salt transport in the Rotterdam waterways and vertical tidal windows. Section 2.4 provides information about sills and summarises the evaluations presented in 2.2 and 2.3 to indicate relevant sill design parameters. Section 2.5 contains the chosen performance indicators per stakeholder. Additional information regarding nature-based solutions and the FoR approach is provided in appendix A.

2.1 The Comparison Tool

The comparison tool is built upon the FoR approach, developed by Van Koningsveld (2003), and uses the same principles to quantify the impact of nature-based solutions per stakeholder. This is done by defining design parameters and performance indicators. The comparison tool, developed by Iglesias (2022), enables these separate outcomes to be related by defining a quantitative trade-off.

Design parameter:	Physical variable of the intervention which can be adjusted.
Performance Indicator:	Variable which describes the impact of the intervention on a specific stakeholder.

The comparison tool consists of the following 7 steps. Steps 1 through 6 describe the FoR approach by Van Koningsveld (2003), whilst the additional 7th step was drafted by Iglesias (2022):

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.
7. Identify dependence between design parameter(s) and performance indicators to trade off multiple performance indicators by the inherent design parameter(s).

2.2 Estuarine Dynamics and Salt Transport in the Rotterdam Waterways

According to Geyer and MacCready (2014), salt intrusion and the salinity gradient are impacted by the following three mechanisms: estuarine circulation, tidal dispersion and net river outflow.

Estuarine circulation occurs due to the difference in density between salt and freshwater. The difference in density creates a baroclinic pressure gradient directed landwards with the highest pressures occurring over the riverbed. The resulting pressure distribution stratifies the water column, creating a seawards (fresh) flux at the surface and a landwards (salt) flux over the bed. The larger the pressure gradient, the further saltwater will intrude due to estuarine circulation (Pietrzak, 2020; Iglesias, 2022).

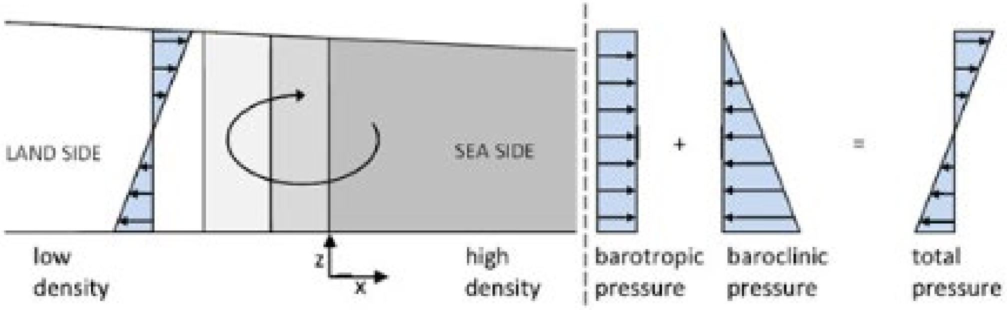

Figure 2.1: Vertical Pressure Distribution causing Estuarine Circulation *(Pietrzak, 2020)*

Tidal dispersion describes the mixing of salt and fresh water during tidal cycles. This process generally leads to more mixed salinity profiles with less variations in salinity over the vertical water column (Iglesias, 2022). The tidal cycles themselves have a more obvious impact on salt intrusion length. Periods of flood lead to saltwater flowing into the estuary, whilst periods of ebb cause both fresh and saltwater to flow back towards the sea (Hydrologic, 2015). Extreme tidal variation can occur under storm surge events. These events lead to significant tidal dispersion and large salt intrusion lengths. Generally, these rare circumstances are classified under type 1 salinisation events (Iglesias, 2022).

Net river outflow (river discharge) has a large influence on salt intrusion in estuaries. In many systems, salt intrusion only takes place once the river discharge fails to provide enough counter pressure to incoming saltwater tides (Hydrologic, 2015). Low river discharges therefore lead to significantly larger salt intrusion lengths, making these low discharge events critical for freshwater supply in estuaries. In the Rhine-Meuse delta, low discharge periods can be defined from values lower than Q=1500 m^3/s at Lobith. This definition is according to a type 0 salinisation event, where low discharges occur under normal tidal conditions (Iglesias, 2022).

Salt transport in the Rotterdam waterways is generally characterized by estuarine circulation. Only in more landward parts of the estuary is the influence of estuarine circulation surpassed by tidal dispersion, wind and other processes (Iglesias, 2022). The salinity gradient of the Rotterdam waterways can be classified as partially mixed to stratified, depending on the river discharge. During lower discharges the estuary exhibits a partially mixed regime, yet this can fluctuate towards being well-mixed under specific conditions (Iglesias, 2022).

Impact of a sill on saltwater intrusion

The relative dominance of estuarine circulation in the Rotterdam waterways indicates that salt intrusion may effectively be reduced through the placement of a sill. The partially-stratified nature of the flow caused by estuarine circulation leads to saltwater travelling over the riverbed. Placing a sill would intuitively halt this salt tongue and cause it to flow upwards, returning and dispersing the salt water along the channel.

The influence of a sill will be considered by assessing the potential effect of the following design parameters: height, length and location. This is discussed in the following paragraphs.

Water depth affects estuarine circulation, with larger water depths inducing a larger bed pressure, thus increasing the magnitude of saltwater intrusion (Iglesias, 2022). Various case studies have confirmed this relation across various estuary types (Chant et al., 2018; Ralston and Geyer, 2019; Veerapaga et al., 2020). It has also specifically been identified within the New Waterway (Hydrologic, 2015).

The inverse of this relationship has also been indicated in the New Waterway and New Meuse, namely that smaller channel depths lead to a reduction in saltwater intrusion (Iglesias, 2022). As an underwater sill reduces channel depth, it is expected that larger sill heights could reduce saltwater intrusion.

In a study done in the Mississippi, the largest sill heights were most effective at arresting the saltwater wedge over a range of river discharges (William McAnally and Pritchard, 1997). From these results it can be stated that sill height may have lesser effect on the length of saltwater intrusion. Instead, higher sills block the saltwater wedge during a wider range of (lower) river discharges.

It is important to note that although studies indicate potential effects of sill height on saltwater intrusion, the actual impact will be highly dependent on the present salinity profile and dominant hydrodynamic processes.

Greater sill length would lead to a larger area of the channel with a raised bed profile. Raised bed profiles lead to smaller water depths, reducing the baroclinic pressure (Pietrzak, 2020*)*. By extending the length of this profile, a greater area would experience a lower pressure, causing a smaller landwards salt bed flux. This reasoning indicates that sill length could have a potential impact on saltwater intrusion.

Sill location is hard to assess regarding the impact on saltwater intrusion. The Rotterdam waterways are highly engineered channels, with little natural variation. There are no significant natural sills which would be effective to amplify, such as in other estuaries like the Mississippi (William McAnally and Pritchard, 1997). Relative to sill height and length, location can be deemed of minor relevance regarding the influence on saltwater intrusion.

2.3 Vertical Channel Design and Vertical Tidal Windows

Since an underwater sill impacts the bathymetry of a channel, it is important to grasp what components influence the vertical design of channels. Port authorities design the vertical dimensions of a waterway to provide the safe entry and exit of vessels. For this, a gross under keel clearance (UKC) is required with respect to a certain nautically guaranteed depth, the maintained bed level (MBL) (PIANC, 2014). This prevents navigating vessels from grounding. For safe and optimal access, the available water depth h_{av} should always be greater than the required water depth h_{req}. The MBLs are therefore optimised according to the following equation: $h_{req} \leq h_{av}$. Figure 2.2 visualises the various components of vertical channel design for vessels.

The gross UKC and MBL are based on safety factors which correct for uncertainties in the actual channel depth, the actual vessel draught and water level. One of these components is the fresh water allowance (FWA) which corrects for density differences over the route of the vessel due to variations in salt concentrations (PIANC, 2014). Furthermore, it is important to note that gross UKC can be expressed statically as a constant value or dynamically as a percentage of static vessel draught. In this research the latter is utilised, as this is prescribed by the port of Rotterdam (Iglesias, 2022; de Jong, 2020).

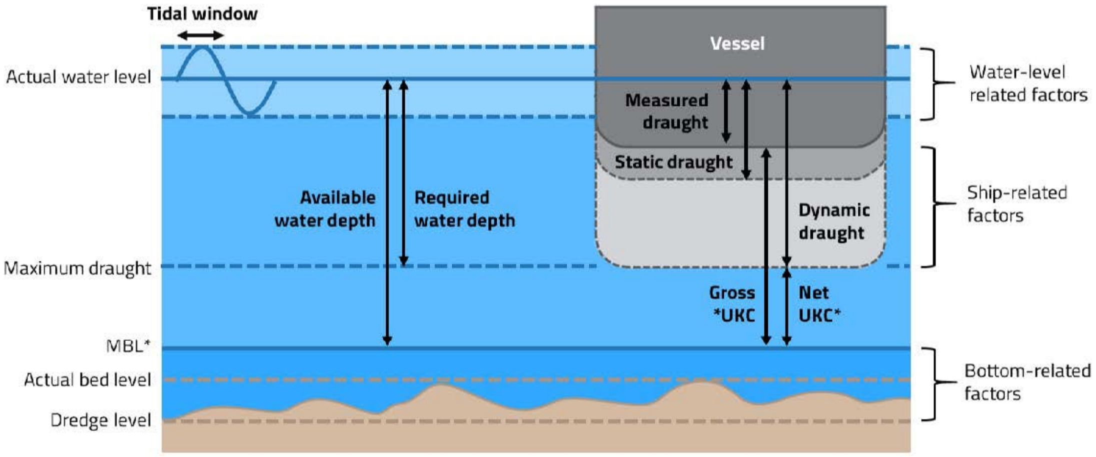

Figure 2.2: *Vertical channel design factors* (Bakker & van Koningsveld, 2023)

Vertical tidal windows

High tides are utilised by port authorities to optimise the access within shipping channels. For vessels with the largest draughts, it is economical to use tidal cycles so that higher MBLs can still provide access. Since these vessels can access or leave their destination during these tidal windows, the port can save on dredging maintenance (Bakker & Van Koningsveld, 2023).

Vertical tidal windows occur when tidally bound vessels comply with the UKC policy of a waterway. This UKC policy effectively determines the sufficient water depth for vessels (Bakker & van Koningsveld, 2023).

Deep-draughted vessels are dependent on these tidal windows and require their presence to operate. Since vertical tidal windows occur during high tides, it is impossible to facilitate tidally bound journeys at any time. Therefore, for optimal turnover and revenue, deep-draughted vessels should be able to make their journey every tidal wave.

For tidal windows to exist, a vessel must comply with the UKC policy. By optimizing the MBL of the waterways according to $h_{req} \leq h_{av}$, a vessel is provided with the best circumstances for vertical tidal windows to occur during its journey. The required and available water depths are described in the following formulas (Iglesias, 2022; de Jong, 2020).

$$h_{req} = T + T * (FWA + UKC) - (HW_{99\%} - \Delta H)$$

Where:

-	h_{req}	Required water depth	[m]
-	T	Vessel draught	[m]
-	FWA	Fresh water allowance	[-]
-	UKC	Under keel clearance	[m]
-	$HW_{99\%}$	Measured high water exceeded by 99% of high water levels	[m]
-	ΔH	Change (lowering) of water level during transit	[m]

$$h_{av} = \eta_{wl} - MBL_{NAP}$$

Where:

- h_{av}	Available water depth	[m]
- η_{wl}	Actual water level at a certain time and location	[m]
- MBL_{NAP}	Maintained bed level relative to NAP	[m]

To assess whether tidal windows exist during transit, both the available and required water depth must be computed dynamically over the vessel route. This is possible by computing both water depths over time and space. When doing so, $HW_{99\%}$, FWA, UKC and MBL_{NAP} may change over space since these depend on the location in the waterways. Meanwhile η_{wl} is dependent on tides and location, thus it may vary over time and space. The lowering of the water level during transit time ΔH is an approximation for a specific voyage. Therefore, it can be neglected when dynamically computing over the vessel route.

It is important to note the distinction between ingoing and outgoing vessels as they experience different vertical tidal windows. Figure 2.3 illustrates this difference, which is due to the relative direction of the ship to the tide. In going vessels can travel along with the incoming tide, whereas outbound vessels sail over the tide. The difference leads to outbound vessels experiencing relatively smaller vertical tidal windows (Iglesias, 2022; de Jong, 2020).

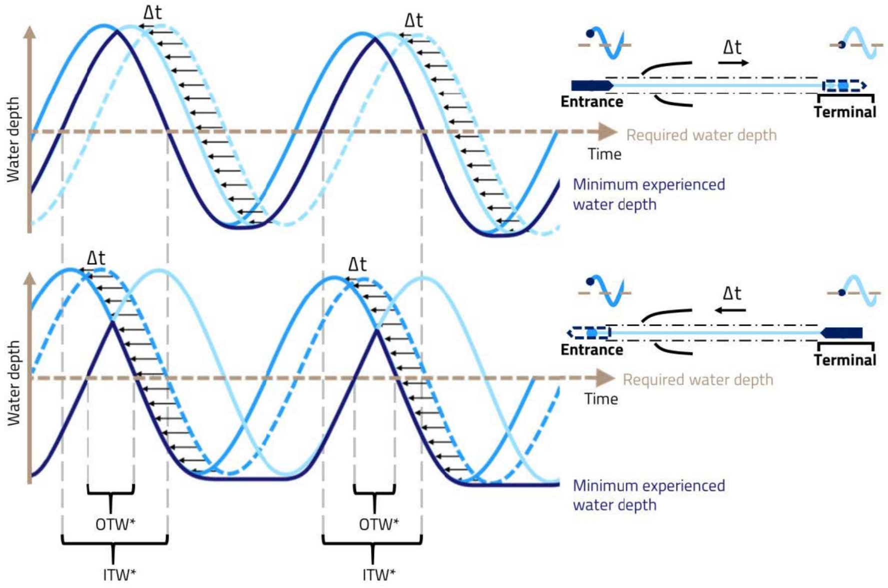

Figure 2.3: *Inbound vs outbound vertical tidal windows (Bakker & Van Koningsveld, 2023)*

Impact of a sill on vertical tidal windows

Underwater sills primarily impact vertical tidal windows, as they alter the bathymetry of the channel bed. The exact effect of a sill is best described through the equations for available and required water depth. For each design parameter (height, length, location) the predicted effect on vertical tidal windows will be illustrated.

Sill height impacts the MBL in the channel, with taller sills leading to an increased MBL_{NAP} and thus a smaller available water depth h_{av}. Since the required water depth h_{req} remains unchanged, the number of vertical tidal windows will decrease. Thus, higher sills are expected to lead to smaller and less sufficient vertical tidal windows.

Since sills locally lead to a lower available water depth h_{av}, these stretches of channel can be deemed critical for the occurrence of tidal windows. Longer sill lengths lead to a longer reduction of h_{av}. This results in a longer stretch of critical channel. Since the critical channel is longer, ΔH will increase as the water level can decrease more whilst sailing over this longer distance. Thus, the required water depth h_{req} to sail over the sill will increase. Longer sill lengths are therefore expected to decrease the number of sufficient tidal windows.

The relation between sill location and tidal windows is relatively simple. Placing a sill in a channel will impact the availability of tidal windows within it. Vessels sailing along routes which include a sill will therefore experience fewer tidal windows.

2.4 Underwater Sill Design

Little research has been done regarding underwater sills and their impact on salt intrusion or port logistics. Some case studies indicate the effects of natural sills, which reduce the progression of salt intrusion in estuaries (Haralambidou et al., 2010; William McAnally and Pritchard, 1997).

Man-made sills are even less researched, yet the case study of the Mississippi river provides relevant background knowledge. Here the US army corps constructed an underwater sill, on top of an existing natural sill, to prevent significant saltwater intrusion due to an extreme period of drought. The measure was effective and arrested the salt wedge, ensuring the safety of the freshwater supply lying further upstream (William McAnally and Pritchard, 1997).

The US army corps constructs this temporary sill periodically for periods with low river discharge. During these low-water seasons, the river cannot hold back the saltwater flux. The sill has been constructed in 1988, 1999 and 2012. Construction plans for a new sill have been in place since 2022 (USAC, 2022).

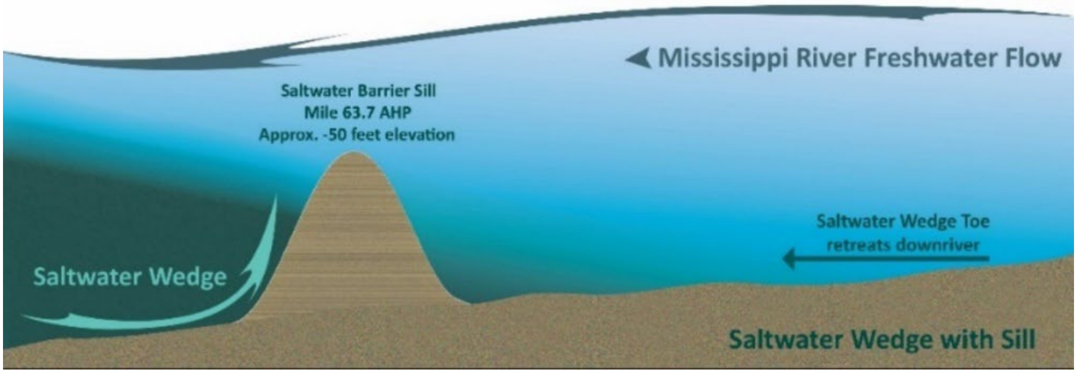

Figure 2.3: *Sill side profile in the Mississippi (USAC, 2022)*

Relevant Sill Design Parameters

From the evaluations presented in sections 2.2 and 2.3, it can be concluded that sill height and length are of greatest relevance regarding the research context. A visual summary of these findings is presented in figure 2.4. Therefore, these design parameters will be utilized to assess the effect of an underwater sill on both freshwater supply and port logistics.

	Freshwater Supply	Port Logistics
Sill Height	↑↑	↓↓
Sill Length	↑↑	↓↓
Sill Location	~	~

Figure 2.4: *Expected effect of sill design parameters per stakeholder* (by C. Hunter)

2.5 Stakeholder Performance Indicators

The previous sections have generally indicated the impact of an underwater sill on two processes within Rijnmond Drechtsteden. Section 2.2 discusses the impact of a sill on salt intrusion, whilst section 2.3 indicates the effects on vertical tidal windows. To formalise the assessment of a sills impact on each stakeholder, performance indicators must be defined. The following two paragraphs illustrate how the impact of a sill can be quantified for the freshwater supply and port logistics in this case study.

Freshwater Supply

The performance of the freshwater supply in a network can be determined by analyzing when freshwater intake points are able to extract water. This occurs when the level of chloride in the water lies below the legal norm for the inlet (Hydrologic, 2015). Legal norms ensure that the extracted water is never too saline for the intended purpose, such as drinking water or industry.

The capacity and thus performance of the network is dependent on how often water can be extracted by the inlets. Therefore, the response of the freshwater network can accurately be represented through the performance indicator *freshwater availability*. This indicator describes the percentage of time during which the salinity content lies below the legal norm and can thus be extracted.

Port Logistics

The logistical operations of ports are complex; therefore, port performance can be assessed in many ways. The study done by Iglesias (2022) assesses performance by considering port efficiency, which indicates delays during operations.

The presence of tidal windows is vital for deep-draughted vessel access in ports. When a tide fails to provide a sufficient tidal window, the vessel is forced to remain at the terminal or anchorage. This induces a delay in the network, which decreases the efficiency of operations.

Therefore, a direct relation exists between the number of tidal windows and port efficiency. To express the effect of a sill on the performance of port logistics, the performance indicator *accessible tides* is used. This is expressed as the percentage of all tides over a period during which sufficient tidal windows occur for deep-draughted vessels.

3. Method

This chapter illustrates the utilized research method. Section 3.1 describes the observed case study: Rijnmond Drechtsteden, listing how both stakeholders are considered within the research. Section 3.2 shows how the comparison tool is applied to the case study. Section 3.3 describes the utilized modelling processes to derive the impact per stakeholder and relate these in a quantitative trade off.

3.1 Case Study

The Haringvliet sluices cause the Rotterdam waterways to be the sole open connection to the sea within Rijnmond Drechtsteden. Therefore from now on, the case study specifically focuses on the Rotterdam waterways.

In this research we consider the port authority and freshwater intake points, which are both active along the Rotterdam waterways. Amongst the many stakeholders in this system, the combined assessment of port and freshwater is particularly relevant. Both stakeholders provide important services to society, yet their vested interests clash within their shared waterways. Previous experiences indicate that port related navigation projects can lead to adverse impacts for regional freshwater supply (Iglesias, 2022). The ethical discussions at the heart of this conflict make the chosen assessment extremely relevant for society. The following paragraphs define how each stakeholder will be considered during the research. These definitions generally follow those of Iglesias, (2022).

Port logistics in the harbour of Rotterdam

The port of Rotterdam is shown in figure 3.1. The port area consists of terminals along the New Meuse and the New Waterway, running from the city to the coast. The Koole terminal is a relevant choice for this study since it lies along the Rotterdam waterways, causing it to be directly impacted by the placement of a sill. Additionally, the largest ships in the vessel fleet are required to access this terminal and do not travel further upstream. These are LR2T class vessels which have a static vessel draught of 15.0 meters (de Jong, 2020).

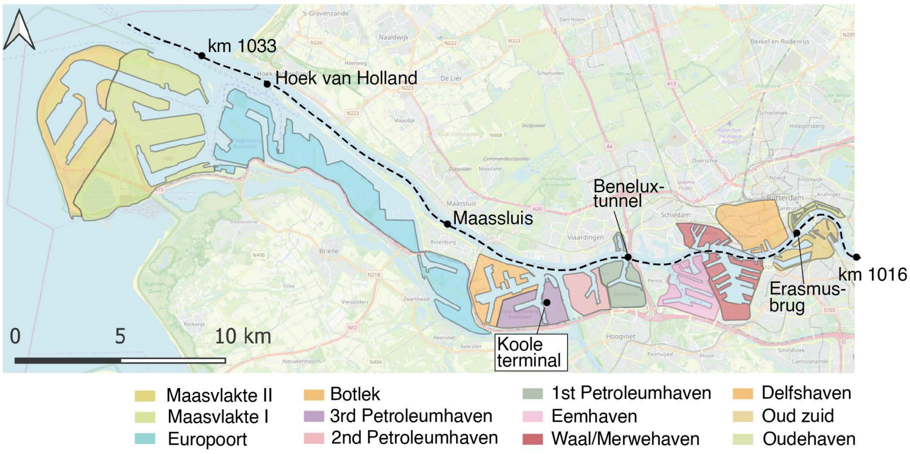

Figure 3.1: *Areas within the port of Rotterdam, including the Koole terminal (Iglesias, 2022)*

The LR2T vessels are deemed critical by the port, and thus determine the MBL of the waterways. The MBL of the New Waterway and New Meuse is maintained according to a dynamic UKC policy of 10%, and a FWA of 1% – 2.5% depending on the stretch of channel.

This results in a dynamic gross UKC policy of 11% - 12.5% of the static vessel draught (de Jong, 2020). Figure 3.2 illustrates the MBLs in meters relative to NAP along the New Waterway and New Meuse. Here we can see that the lower 11% corresponds to the seawards stretch of -16.2m, whilst the 12.5% results in a landwards MBL of -16.4m. The profile after the Benelux tunnel is characterized by the trapjeslijn. This project gradually raised the MBLs in steps to combat further salt intrusion in the estuary.

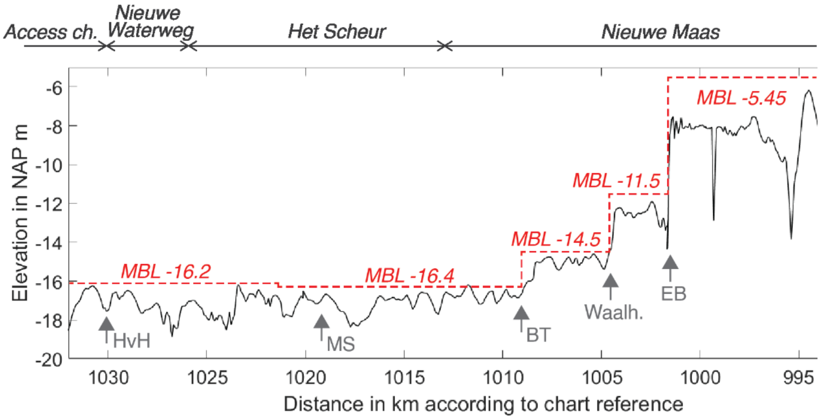

Figure 3.2: *Current riverbed bathymetry in the Rotterdam waterways (Iglesias, 2022)*

The port will be assessed solely by observing the effects on vessels travelling to and from the Koole terminal. The effect on port processes is further simplified by only considering the tidal windows which occur for LR2T class vessels under the specified UKC policy.

Freshwater supply in Rijnmond Drechtsteden

The freshwater supply in Rijnmond Drechtsteden consists of a complex network of inlets, provisioning water for a range of users such as agriculture, industry and drinking. This study opts to observe the freshwater inlet at Boerengat, which extracts water for agricultural purposes. Figure 3.3 illustrates the location of the inlet and shows the salinity profile in PSU for the area during a type 0 salinisation event (Q=1000 m^3/s at Lobith).

According to Iglesias (2022) the Boerengat inlet extracts water at a depth of -2.5 m NAP, therefore salinity will be determined at this depth. The legal standard for chloride content at the Boerengat inlet is 400 Cl- mg/L (Hydrologic, 2015). The limit is surpassed during this particular salinisation event, as salinity levels above 0.3PSU (540 Cl- mg/L) intrude past the inlet.

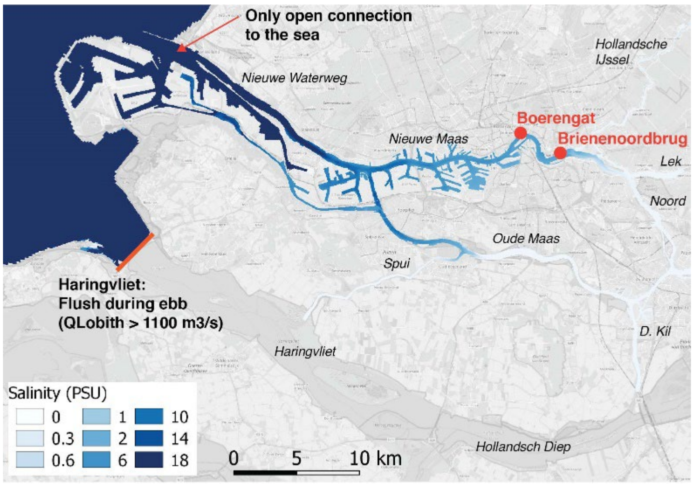

Figure 3.3: *Location of the Boerengat freshwater inlet (Iglesias, 2022)*

Salinisation Event

Various salinisation events can take place depending on meteorological and tidal conditions. These affect the magnitude of salt intrusion within the estuary and the impact on freshwater extraction. This research analyses the circumstances induced by a type 0 salinisation event, which occurs under severely low river discharge ($Q < 1500$ m^3/s at Lobith) with no wind setup. This study will specifically consider a low discharge event of $Q = 1100$ m^3/s at Lobith.

3.2 Configuring the Comparison Tool

The comparison tool defined by Iglesias (2022) is used as a framework to develop a quantitative trade off between port logistics and freshwater supply. The following steps illustrate how this approach has been adapted to the research case study.

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

The strategic objective for both stakeholders can be defined as follows: Protect the freshwater system in the region through the placement of a sill, whilst facilitating a competitive position for the port of Rotterdam.

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

The operational objective of the port can be defined by their own requirements. The port strives to provide suitable access to the entire (inbound) vessel fleet. This facilitates optimal port operations and efficiency.

The operational objective of the regional freshwater supply falls in line with the goals set by the national delta program: protect and maintain the freshwater network for crucial users. This can be achieved by reducing the time periods which exceed the legal salinity norm.

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).*

Due to the pioneering nature of this research, simplified performance indicators have been chosen for both stakeholders. By means of an initial assessment, an idealised relation should be obtained between the sill design and each stakeholder. This is predicted to be sufficient for illustrating the general impact of a sill in the research context. Further reflection regarding the choice of performance indicators and modelling tools is presented in chapter 5.

Quantitative State Concept – Port Logistics:

The performance of port logistics is assessed using the percentage of *accessible tides*. This parameter indicates the percentage of tides for which a vessel has access to its destination over a set time period. This indicator can be quantified by using simplified simulations in the nautical traffic model OpenTNSim. This model couples a geo-spatial network with hydrodynamic data, which allows the effect of MBL changes to be assessed regarding nautical processes (Bakker & van Koningsveld, 2023).

The operational objective of the port can be expressed in terms of accessible tides according to their own specifications. It strives to provide access to tidally bound, inbound vessels for 99% of tides. The access of outbound vessels is not prescribed (de Jong, 2020).

Quantitative State Concept – Fresh Water Supply:

Fresh water supply is assessed using the performance indicator *freshwater availability*. This describes the percentage of time during which the salinity content lies below the legal norm and can thus be extracted. The availability of freshwater at Boerengat can be quantified by a numerical study using Delft 3D Flexible Mesh (DFM) simulations. The DFM model facilitates the simulation of an idealised estuary in 3D which mimics the Rotterdam waterways.

4. *Specify how to benchmark the performance of a design.*

The performance of each sill design can be benchmarked by comparing each performance indicator to their base values for the reference case. The reference case reflects the present bathymetry of the waterways.

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.*

Step 5 functions in an iterative manner where the intervention procedures (sill designs) are drafted based upon their respective benchmark performance.

It is important to note that this study will conduct steps 4 and 5 in series, instead of in a parallel fashion as defined by Iglesias (2022) and van Koningsveld (2003). Since the effects of bed shallowing are generally too severe for port logistics, this study specifically aims to investigate sill designs which are acceptable for the port. To achieve this, sill designs are first limited to cases which provide sufficient accessible tides. These designs are then assessed regarding their impact on freshwater availability.

6. *Evaluate the effectiveness of the decisions made by reflecting on the operational and strategic objectives.*
7. *Identify dependence between design parameter(s) and performance indicators to trade off multiple performance indicators by the inherent design parameter(s).*

The effectiveness of the sill designs is discussed in chapter 5. Both the individual dependencies and the resulting trade offs are presented in chapter 4. Figure 3.4 illustrates the aforementioned steps of the configured comparison tool in chronological order.

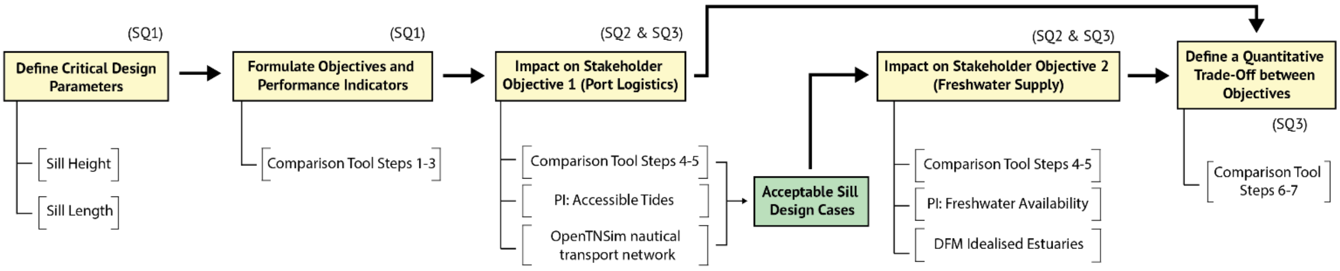

Figure 3.4: *Adapted comparison tool for the research context* (by C. Hunter)

3.3 Modelling Procedure

This subsection further describes the utilized modelling procedures which lead to the results presented in chapter 4.

Port logistics: **OpenTNSim nautical traffic network**

OpenTNSim utilizes geospatial networks to model vessel traffic within ports. These networks are discretized into nodes and edges, representing the paths taken by sailing vessels. Figure 3.5 illustrates the network which between the anchorage sites at sea and the berths at the Koole terminal. The network is coupled to hydrodynamic data. This allows the model to determine over time and space whether a specific vessel has a tidal window to reach its destination. The tidal windows are computed using the combined vertical and horizontal conditions, which depend on available water level and current velocity respectively.

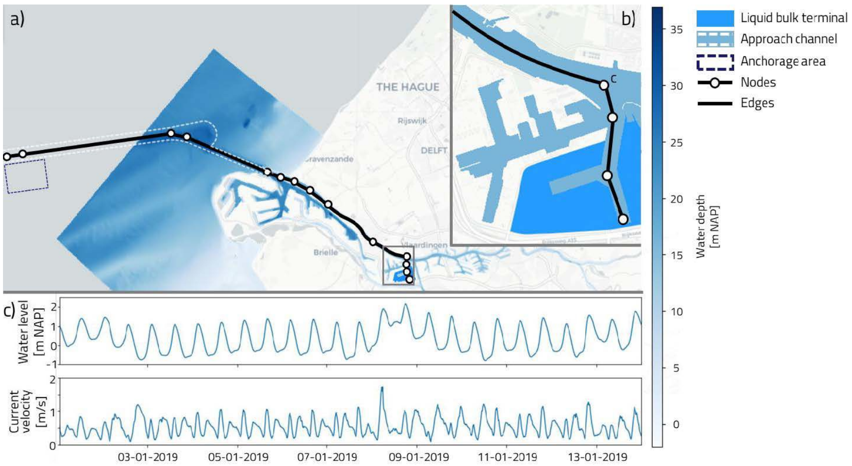

Figure 3.5: *OpenTNSim network for the Koole terminal* (Bakker & van Koningsveld, 2023)

The following steps have been undertaken to model the impact on the accessibility of the port:

1. ***Insert sill in geospatial network***

Each node in the network has an assigned MBL to represent the bathymetry of the estuary. To insert a sill into the present bathymetry, additional nodes and edges are required which represent the location, height, and length of the sill.

The start of the sill has been fixed at an existing node which lies at Hoek van Holland, near the estuary mouth. Then depending on the length L of the sill, a new node is inserted at a distance L landwards along the network. The sill height H is appended to all nodes between the start and end, resulting in a sill starting at Hoek van Holland with height H and length L. Figure 3.6 illustrates the potential locations for the sill.

Figure 3.6: *Sill start node and potential length in OpenTNSim network* (by C. Hunter)

2. *Compute tidal windows and accessible tides for LR2T vessels (T=15.0m)*

Using OpenTNSim scripts, it is possible to determine the occurring tidal windows during a period of hydrodynamic data. In this study, measured hydrodynamic data from 01/01/2019 to 29/01/2019 is utilized, which contains 55 tidal cycles. The analysis is conducted for the largest, tidally bound vessels (LR2T) which have a draught of 15.0 meters and sail at a speed of 4.5 knots.

In this study tides are deemed accessible when tidal windows exist for at least 1 hour. Therefore, the number (or percentage) of accessible tides can easily be determined by overlaying the tidal window and tidal cycle periods.

Freshwater supply: Idealized Estuaries in DFM

The idealized estuary modelled in DFM provides a benchmark regarding salt intrusion to assess the impact of sill designs. This estuary has been constructed such that it mimics the properties of the Rijnmond Drechtsteden estuary, whilst also taking the type 0 salinisation event into account. This results in the following boundary conditions, shown in table 3.1. The chosen modelling process simplifies some processes. Average tidal conditions are utilized to achieve dynamic equilibrium, therefore spring-neap cycles are not taken into consideration. The DFM model also assumes hydrostatic pressure, therefore it does not process non-hydrostatic behaviour such as internal waves.

Table 3.1: *Boundary Conditions for the Idealized Estuaries*

Tidal Amplitude	Landwards	$A = 1$ m
Tidal Period	Landwards	$T = 12$ hrs
River Discharge	Seawards	$Q = 1100\ m^3/s$
Oceanic Salinity	West	$s_o = 30$ ppt
Landward Salinity	East	$s_L = 0$ ppt

To determine the impact of the chosen sill designs on the freshwater availability, the following steps must be taken:

1. *Generate new Estuaries*

The chosen sill designs can be inserted into the xyz data profile of the reference case, which is shown in figure 3.7. These new bathymetries can then be run using the defined boundary conditions to determine the hydrodynamic effects of the sill designs.

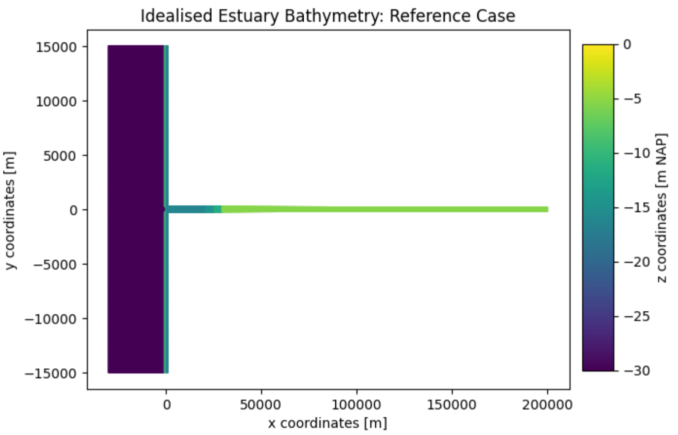

Figure 3.7: *Reference Bathymetry for the Idealised Estuary*

2. Determine resulting salinity signal at Boerengat intake

The salinity signal is comprised of the salt content over a 24 hour period. The signal occurring at the location of the Boerengat intake can be extracted from the output of the DFM runs. The location of the intake is specified at a depth of -2.5m NAP, and at a point 32km landwards from the estuary mouth.

3. Compute freshwater availability

Finally freshwater availability can be computed by extracting the duration of the salinity signal for which the salt content lies below the legal norm of 400 Cl- mg/L. This can then be expressed as a percentage of the entire signal duration.

Quantitative trade-offs:

The trade-off relations between each design variable and the performance indicators can be constructed using the data from the OpenTNSim and DFM outputs. This is done by fitting 3D functions over the obtained values for accessible tides and freshwater availability per design case, The resulting trade off relations allow us to determine which sills are optimal for the stakeholders.

4. Results

This chapter contains the obtained results from the method described in sections 3.2 and 3.3. Section 4.1 lists the findings from an initial tidal event analysis. Section 4.2 lists the results of the sill bathymetries on accessible tides, plus the chosen sill design cases. Section 4.3 lists the results of the sill designs on freshwater availability. Section 4.4 lists the quantitative trade off relations developed using the model outputs.

4.1 Initial Tidal Event Analysis

Before researching the effect of sill design on tidal windows, an initial analysis was conducted to get indications of possible sill heights. LR2T vessels are required to access the terminal for 99% of tides. Since these vessels are tidally bound, the highest water levels during a tidal cycle are critical for access.

By adjusting the MBL at the sill start location, an initial analysis was conducted to determine the critical (highest) MBL where (partially loaded) LR2T vessels have access for 99% of tides. Figure 4.1 illustrates the probability distribution of highest available water depths in the dataset, under the critical MBL of -15.6 m NAP. This nicely showcases the stochastic nature of tidal events, with the distribution curves exhibiting almost normal distributions. MBLs above -15.6m led to a reduction in access for LR2T vessels and are therefore suboptimal for the port.

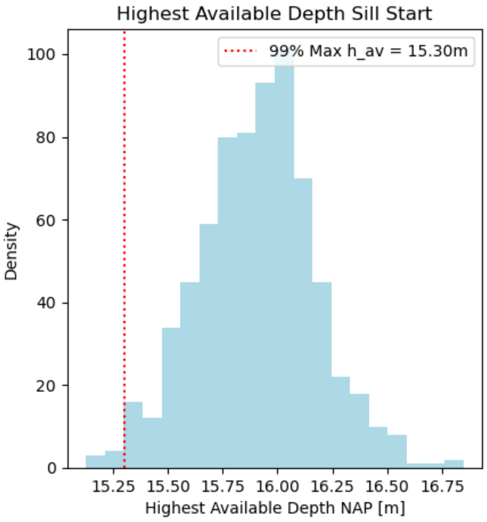

Figure 4.1: *Probability distribution functions for highest available depth at sill start node*

The results are relevant for the sill design height, but not final. To describe the effect of a sill on port access correctly both sill height and length must be considered. Instead of only viewing the vertical access condition ($h_{req} \leq h_{av}$) at a single point, tidal windows must be computed over time and space within the network. This is presented in the following section.

4.2 Effect of Sill Design on Accessible Tides

Utilizing the modelling procedure described in section 3.3, the effect of sill height and length has been determined for the amount of accessible tides. The reference case was computed first to determine what the access is for Inbound and Outbound vessels under the current bathymetry. This led to 98.18% and 83.64% for inbound and outbound LR2T vessels respectively. This already violates the 99% inbound requirement of the port. Figure 4.2 visualizes the inbound reference case, where 1/55 tides fail to exhibit a cumulative tidal window period greater than an hour.

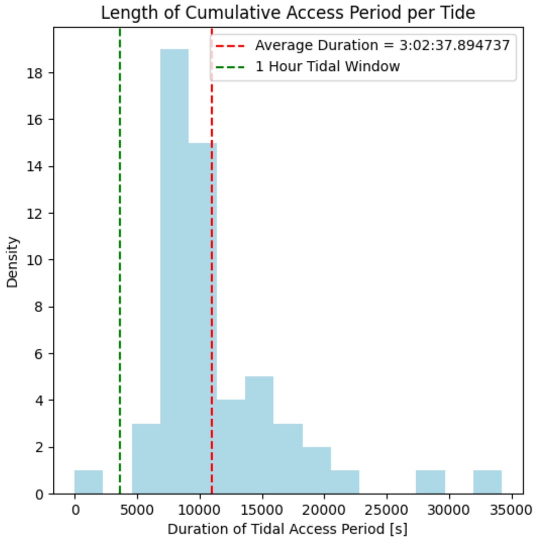

Figure 4.2: *Tidal windows and accessible tides for the inbound reference case: no sill*

To determine the effect of both sill height and length, various values and combinations were trialed. From these tests three general properties could be deduced:

1. Inbound and outbound vessels respond equally to changes in the design parameters.
2. Outbound vessels consistently experience lower access levels.
3. Sill height has a relatively larger influence on accessible tides than sill length. Therefore, three acceptable sill heights were initially drafted, after which a diverse range of lengths was chosen.

Chosen Sill Cases

Sill heights of 0.1m correspond with the reference situation, yet every considered case fails to fulfil the 99% inbound requirement. To work with these results and explore a more flexible stance by the port authority, a wider range of percentages has been considered. 100-90% could be considered acceptable, 90-80% possible, and lower than 80% unacceptable. It is important to note that percentages lower than 99% have not been proven to be acceptable.

From sill heights of 0.3m and larger, unacceptable levels of tidal accessibility (<80%) are present. This led to the selection of 0.1m, 0.2m and 0.3m as relevant sill heights, indicating that there is extremely limited vertical space for sills in the new waterway. Sill length has virtually no impact on accessible tides for heights in this range, allowing a wide range of lengths to be considered: 2000m, 5000m and 10000m. The impact per height and length is presented in table 4.1.

Table 4.1: Percentage of accessible tides per sill design

Percentage of Accessible Tides for LR2T Vessels (T = 15.0m)								
MBL	**16.2**		**16.1**		**16.0**		**15.9**	
L/H	**0**		**0.1**		**0.2**		**0.3**	
Bound	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
0	98.18	83.64	x	x	x	x	x	x
2000	x	x	98.18	83.64	89.09	70.91	76.36	52.73
5000	x	x	98.18	83.64	89.09	67.27	74.55	52.73
10000	x	x	98.18	83.64	89.09	67.27	74.55	52.73

An additional design case was considered where the MBL was lowered landwards after the sill till the terminal. According to the theory on tidal windows, this extra depth should aid outbound vessels in complying with vertical tidal window policy. Since outbound vessels experience shorter high tides, they are more dependent on the MBL of the channels. Table 4.2 illustrates the results of the design cases, which are in line with the hypothesis.

Table 4.2: Percentage of accessible tides per sill design, with a deeper port (MBL = -17.1 NAP)

Percentage of Accessible Tides for LR2T Vessels (T = 15.0) - Port MBL = -17.1 m NAP								
MBL	**16.2**		**16.1**		**16.0**		**15.9**	
L/H	**0**		**0.1**		**0.2**		**0.3**	
Bound	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
0	98.18	100	x	x	x	x	x	x
2000	x	x	98.18	100	89.09	90.91	76.36	78.18
5000	x	x	98.18	96.36	89.09	80.00	74.55	65.45
10000	x	x	98.18	90.91	89.09	72.73	74.55	52.73

The additional depth after the sill has zero effect for inbound vessels. All inbound access percentages remain equal to the original values in table 4.1. The access for outbound ships is significantly improved across all sill designs, including the reference case. This indicates that lower MBLs in the terminal are effective at improving outbound tidal window access and can counteract the negative consequences of a sill.

In contrast to the original response, outbound vessels now exhibit a larger sensitivity to changes in sill length. Since the terminal MBLs are now less critical, the bathymetry of the sill is likely to have a larger impact on vessel access.

4.3 Effect of Sill Design on Salt Intrusion

The acceptable sill designs have been modelled with DFM, following the procedure listed in section 3.3.2. The salinity signal for both the reference case (left) and h=0.3m, L=10000m (right) is shown in figure 4.2. The signals exhibit two peaks which greatly exceed the legal norm of 400 Cl- mg/L. Each peak lasts approximately 3 hours, leading to a freshwater availability of 73.95% and 74.03% respectively over the entire signal. Both peaks are identical due to the assumption of average tidal events.

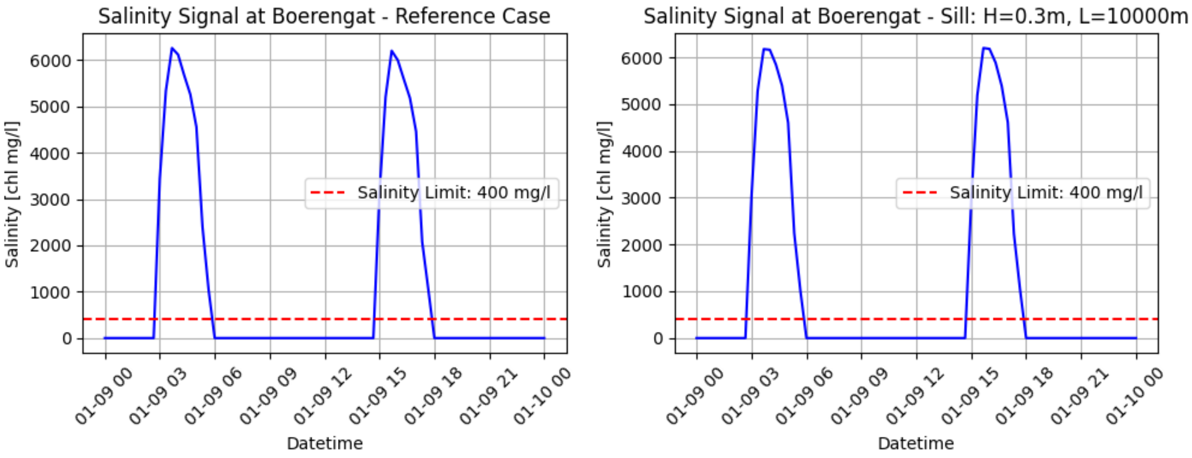

Figure 4.2: *Salinity signals for the reference case (left) and h=0.3m, L=10000m (right)*

The freshwater availability is shown per case in tables 4.3 and 4.4. From these values it becomes clear that the sill designs have a minor influence on salt transport and freshwater availability. The sill designs generally improve freshwater availability by +0.2% to +0.8%. Changes in height or length do not lead to consistent changes in freshwater availability. Despite this, the results are generally in line with the expectations: although the influence is small, the sills reduce salt intrusion in the estuary.

The cases with the dredged port exhibit more consistent relations regarding sill height and length. The responses of this combined intervention are in line with the hydrodynamic theory yet are again extremely small in magnitude. Since no reference case was computed for these design cases, no comment can be made regarding the impact of the sills alone. The combined intervention does however lead to slightly lower availability compared to the original sill cases.

Table 4.3: Freshwater availability percentages per sill design, reference port: MBL = -16.4m NAP

Freshwater Availability [%] during an Average Tide: Reference port MBL = -16.4m NAP				
MBL	**16.2**	**16.1**	**16.0**	**15.9**
L/H	**0**	**0.1**	**0.2**	**0.3**
0	73.95	x	x	x
2000	x	73.99	73.97	73.97
5000	x	73.97	73.99	73.97
10000	x	73.98	74.00	74.03

Table 4.4: Freshwater availability percentages per sill design, dredged port: MBL = -17.1m NAP

Freshwater Availability [%] during an Average Tide: Dredged port: MBL = -17.1m NAP				
MBL	**16.2**	**16.1**	**16.0**	**15.9**
L/H	**0**	**0.1**	**0.2**	**0.3**
0	/	x	x	x
2000	x	73.84	73.86	73.89
5000	x	73.88	73.88	73.90
10000	x	73.91	73.95	73.98

4.4 Quantitative Trade-Off Relations

Using the results presented in sections 4.2 and 4.1, trade off curves have been created according to the procedure set out in section 3.3. The following curves have been made by keeping one design parameter constant and plotting the resulting trade off between performance indicators for the other design parameter. The entire set of trade off curves is provided in appendix B.

Standard sill design cases

Figure 4.3 presents inbound and outbound trade off curves for constant sill lengths, and varying sill heights. As shown by the vertical functions, sill height only impacts accessible tides. The percentage of freshwater availability remains nearly constant for all possible heights in the range of the data points. Figure 4.4 presents inbound and outbound trade off curves for constant sill heights, and variable sill lengths. Again, all curves showcase no variation over the x axis, illustrating the same lack of effect on freshwater availability.

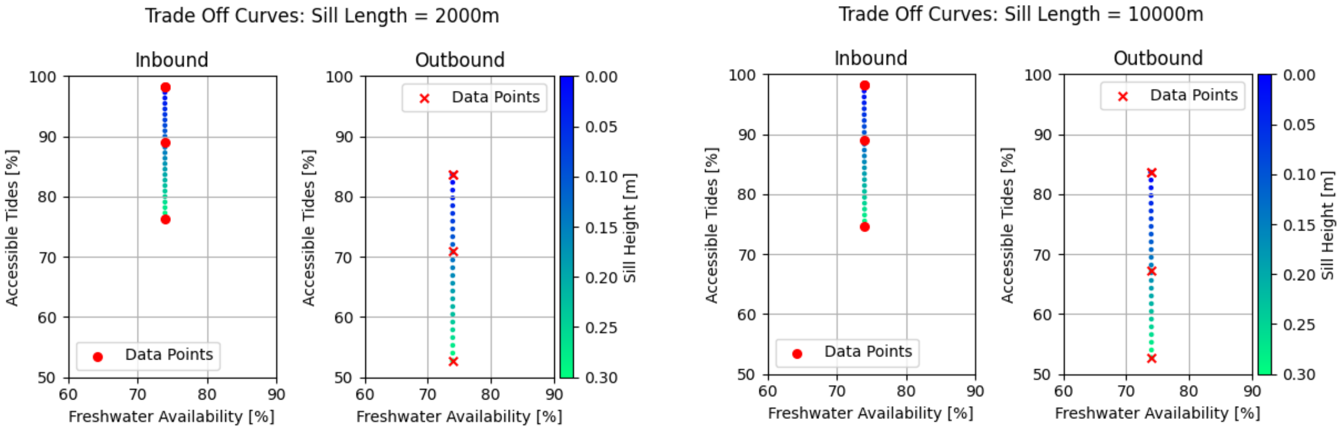

Figure 4.3: Left: Trade off curves for L = 2000m, Right: Trade off curves for L = 10000m

Sill length has relatively little influence on accessible tides compared to sill height. This is shown in figure 4.4 as all data points (2000, 5000, 10000) are in proximity. The 0.1m case (left) shows no response for all values as they all equal the reference case. The 0.3m case shows that the considered sill lengths reduce access relative to the reference case, yet all by the same amount. This indicates that the access reduction is likely due to the shared height of 0.3m, but that the varying lengths have little effect.

To further asses the influence of sill length, an additional design case was drafted for the 0.3m sills (right figure). This extra data point represents a bed shallowing of 0.3m from Hoek van Holland till the Benelux tunnel and has a ‘’sill length’’ of 21000m. The measure impacts accessible tides for both inbound and outbound vessels, yet both bounds exhibit no changes in freshwater accessibility. This strongly indicates that the sill heights are too small to improve freshwater availability.

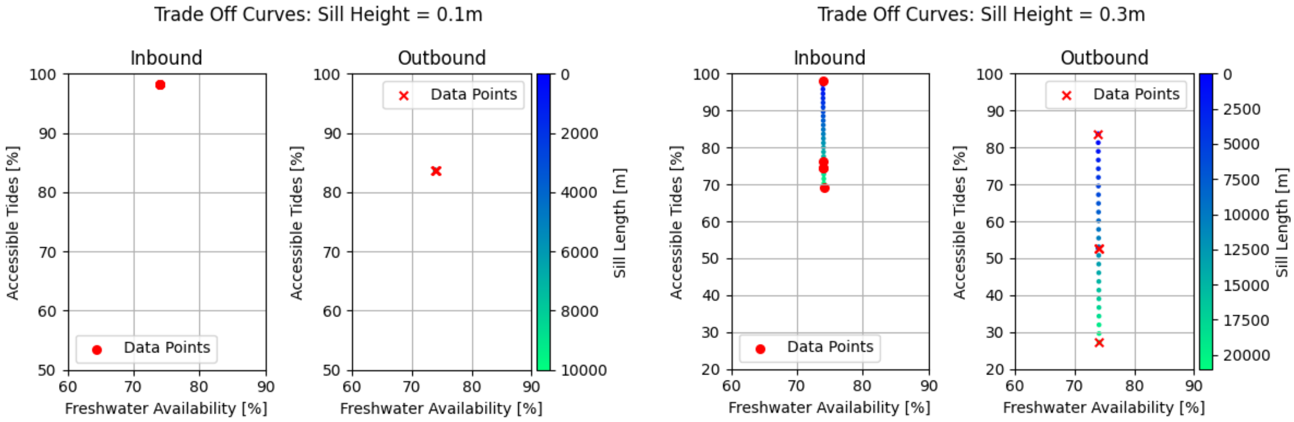

Figure 4.4: Left: Trade off curves for h = 0.1m, Right: Trade off curves for h = 0.3m

Sill design cases with dredged port

Since the dredged port has no impact on inbound vessels, trade off curves have only been constructed for outbound vessels. Figure 4.5 illustrates the resulting relation for sill height and sill length. The resulting trade offs mirror those of the standard cases, as neither design parameter influences freshwater availability significantly.

Differences in the dredged and original cases are found when comparing the accessible tide response. Dredged cases generally exhibit higher access percentages under the chosen height and length ranges. Sill length also has a greater impact on accessible tides in dredged cases.

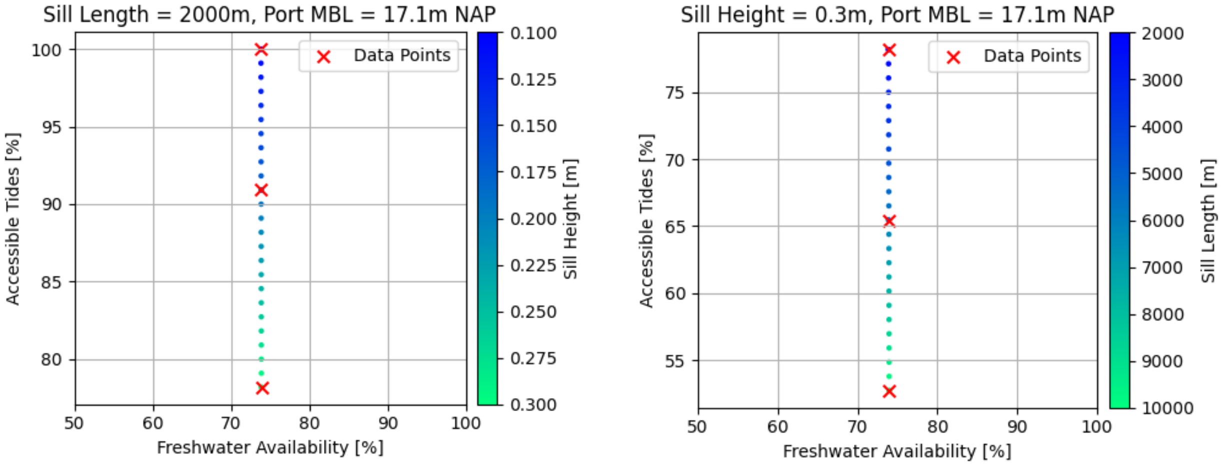

Figure 4.5: Left: Outbound trade off curve for L=2000m, Right: Outbound trade off curve for h = 0.3m

5. Discussion

This chapter reflects on the chosen methods and obtained results presented in chapters 3 and 4. Section 5.1 reflects on the discovered trade off relations following step 6 of the comparison tool. Section 5.2 discusses the consequences of the chosen approach. Section 5.3 evaluates the relevance of the results regarding current literature and the context of the case study.

5.1 Evaluating the Trade Off Relations

All trade off relations constructed in this study exhibit little to no variation in freshwater availability. This static response leads to none of the curves presenting a concrete trade off. Every choice in the design parameters results in nearly the same degree of freshwater availability, leaving nothing to be traded off when opting for a certain percentage of accessible tides. The lack of relevant trade off relations is caused by the chosen operational objective of the port. The effects of this objective can be described by following step 6 of the comparison tool:

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

The discovered trade off relations indicate that it is difficult to design sills which comply with both operational objectives. This study aimed to investigate sill designs which are feasible for the port by adhering to its operational objective (tidally bound, inbound access for 99% of tides). To comply with this objective the range of sill heights had to be severely restricted. These restricted sill heights have no significant impact on freshwater availability. Therefore, none of the chosen sill designs can fulfil the operational objective of the freshwater supply (reduce salinisation periods). By failing to meet both operational objectives, the drafted sill designs also fail to meet the overarching strategic objective.

If larger sill designs were drafted which did impact freshwater availability significantly, these designs would almost certainly lead to far from acceptable access percentages for the port. These designs would thus also fail to satisfy the strategic objective. The mutually exclusive nature of the operational objectives makes it highly difficult to design sills which reach the strategic objective of both stakeholders.

Although the designs fail to achieve the strategic objective, the dredged port designs propose some interesting prospects for the port authority. The improved outbound access leads to an almost unnoticeable reduction in freshwater availability. Despite this, it is too early to state that the sill designs are effective at counteracting the consequences of dredging the New Waterway and 3rd petroleum harbour. Since no reference case was considered for the dredged port, no accurate comments can be made regarding the sole impact of the sill designs. This would be relevant for further investigation.

5.2 Consequences of Approach

Limited relation between design parameters and performance indicators

Since the range of sill height was limited to the operational objective of the port, an incomplete relation has been constructed in the trade off curves. To fully portray the effect of sill height and length on accessible tides and freshwater availability, a wider range of height values must be considered.

This justifies not extrapolating the trade off functions beyond the range of the data points. The relation between the design parameters and the performance indicators may be vastly different when considering a larger range of sill heights. According to the theory, the higher the sill the more saltwater it should block. This would result in an inverse relation between accessible tides and freshwater availability, potentially exponential or polynomial.

Performance indicators and modelling techniques

Performance indicators determine how an intervention performs. This makes it critical to be aware of their limitations, otherwise incorrect conclusions can be drawn. Regarding this research, both performance indicators fail to process the full (stochastic) nature of hydrodynamic events over time. Processes such as the spring-neap cycle or wind setup have not been considered, which have can have a decisive impact on water levels and saltwater intrusion. Climate change is also not considered by the chosen indicators. The consequences of rising sea levels and extreme river discharge fluctuations may lead to more critical events in the future.

When these extreme events occur for prolonged periods of time, critical circumstances are created which severely impede stakeholders. The chosen performance indicators (accessible tides, freshwater availability) only take a percentage of all events into account. They both fail to capture specifically when, and how long these random events take place in the system. Research shows that port accessibility is an inaccurate performance indicator for port performance. The indicator fails to consider the cascading effects between vessels which arise during interactions between vessels and port infrastructure (Bakker & Van Koningsveld 2023). Meanwhile freshwater supply is more accurately assessed when taking inlet storage capacity and discharge rates into account across the entire network (Hydrologic, 2015). This way critical periods of water shortage can be identified in the network.

Instead of accessibility, other parameters can be used such as time averaged waiting times (Iglesias, 2022). This parameter takes delays into account which are caused during intra-vessel and infrastructure interactions. Simulations in OpenTNSim facilitate this assessment. To better assess the freshwater supply, more realistic modelling approaches could be applied using DFM or OSR models.

However, using accurate performance indicators requires extensive modelling techniques. These can take a significant amount of time and computing power. The result of this dependency necessitates critical reflection of the research goal, and the combination of models and performance indicators which achieve this best. In this study the chosen combination of (simplified) models and performance indicators still manages to present a decisive outcome regarding the research context. Therefore, although the outcome is idealized, it does effectively answer the research questions via a pioneering approach.

5.3 Relevance of results

Current literature

The results of this study are highly relevant for WP7.3 and the wider community researching nature-based countermeasures to salt intrusion. Since the idealized results strongly indicate that sills are not a feasible solution in the new waterway, further more extensive methods are not recommended. Instead, these results serve as a signal to investigate the potential of other nature-based measures which are better suited to the case study context.

Case study

It is important to recognize the relevance of the case study when interpreting the results of this research. The Rotterdam waterways are highly engineered due to the required functionality of the port. The design MBL of the channels is dictated by the vessels which sail through them. The port ensures to dredge and maintain these MBLs so that their operational objective is met.

The opportunities for sills are extremely limited due to these requirements, therefore one may consider adjusting the vessel fleet to allow for larger sills. This may appear to be a relevant solution, but it fails as the port only dredges to accommodate the critical vessel. By opting for a smaller vessel draught, the port no longer has to dredge to the original level. This leads to bed shallowing across the channel until the new critical MBL is met. The relative sill height is now comparable to the original case. Salt intrusion may be reduced due to the shallower MBL, but the contribution of the sill remains the same as its relative height is unchanged. This process is visualized in figure 5.1.

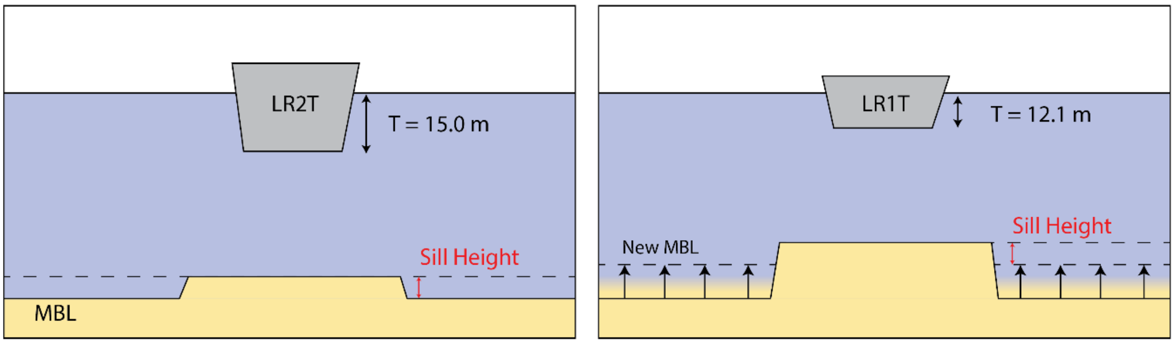

Figure 5.1: *Result of smaller vessel class and taller sill* (by C. Hunter)

From this process it can be concluded that it is irrelevant to construct ‘tall’ sills in actively dredged waterways such as the new waterway. Estuaries with natural bathymetries are more suitable for sill construction. These channels are not maintained at a critical depth, therefore there is space over the vertical for a sill to be constructed. A prime example of this is the Mississippi, where a tall sill effectively reduces saltwater intrusion (William McAnally and Pritchard, 1997; USAC, 2022). These two cases indicate the importance of identifying the type of estuary when drafting nature-based solutions for salt intrusion.

Instead of opting for a smaller design vessel in the channels, it may be effective to downscale the access limit set by the port. According to data collected by de Jong (2020), only 6 LR2T vessels sailed to the Koole terminal over a period between Jan 2015 – Feb 2020. This is a minor fraction of all vessels which travelled to the terminal. Therefore, it may be feasible for the port to adhere to lower access percentages for these vessels whilst maintaining its standard of operations. Downscaling the access limit would effectively generate more room for nature-based solutions to satisfy both operational objectives, thus generating a positive impact in the system.

6. Conclusion and Recommendations

6.1 Conclusion

The overarching goal of this study was to investigate the effects of sills as a nature-based measure against salt intrusion within Rijnmond Drechtsteden. This was done by assessing the impact of sills on the regional freshwater supply and the performance of the port. Firstly, an extensive literature review provided relevant knowledge to determine the critical design parameters for underwater sills within this research context. Both sill height and sill length were deemed most relevant regarding their impact on both stakeholders, answering SQ1.

Then by adapting the comparison tool defined by Iglesias (2022), the research methodology was defined, answering SQ2. Strategic and operational objectives were defined for the port authority and freshwater supply. These objectives could then be assessed using the chosen combination of performance indicators and modelling techniques. Port performance was estimated using port accessibility in OpenTNSim runs, whilst freshwater supply was quantified in freshwater availability using an idealized estuary simulated in DFM. Sill designs were selected based on the operational objective of the port. This was done to focus the research on designs which are acceptable for the port authority. The filtered designs consisted of combinations of 3 sill heights (0.1m, 0.2m, 0.3m) and 3 sill lengths (2000m, 5000m, 10000m).

The outcome of this method provided results per stakeholder, which could then be combined to form trade off curves. Freshwater availability remained nearly constant for all design cases. Meanwhile accessible tides responded heavily to changes in sill height and lightly to changes in sill length. This resulted in linear trade off curves which all indicated zero response in the freshwater system. These resulting trade off relations answer SQ3.

From the results it could be concluded that the filtered sill heights and lengths were too small to have a noticeable impact on freshwater availability. The trade off relations indicated that sills are ineffective in this case study, as designs cannot satisfy both operational objectives.

6.2 Recommendations

The following recommendations can be made to the research community investigating nature-based countermeasures to salt intrusion. These suggestions are also directed at the Rotterdam port authority and the freshwater supply in the Rijnmond Drechtsteden region.

1. Investigate other nature-based solutions than sills for the Rotterdam waterways. The active dredging requirements lead to sill construction being ineffective.

2. Identify the type of bed bathymetry in an estuary to assess whether underwater sills could be an effective nature-based counter measure to salt intrusion.

3. Investigate the downscaling of access percentages as the port's operational objective. This could potentially provide more room for nature-based solutions to comply with the port's operational objectives.

4. Further investigate the impact of dredging the 3rd petroleum harbour for port logistics and saltwater intrusion. This has potential to improve outbound tidal access without severely increasing saltwater intrusion in the waterways.

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Appendix A: Complete Literature Review

A.1 Building with Nature and Nature-Based Solutions

The building with nature design philosophy has been gaining traction over the past years. Comparable initiatives such as ‘Working with Nature’ (PIANC, 2011), ‘Engineering with Nature’ (USAC, 2011) and ‘Building with Nature’ (Nieboer & Ovink, 2018) have arisen which all aim to better integrate infrastructure into the surrounding environment.

The building with nature philosophy is defined by de Vriend, et al. (2014) as, ‘’meeting society’s infrastructural demands by starting from the functioning of the natural and societal systems in which the infrastructure is to be realised’’ (p. 32).

Implementing this philosophy necessitates a thorough understanding of the embedded natural and social systems. This inherently leads to a complex multi-actor approach where stakeholder interests need to be balanced to achieve a sustainable solution. Five design steps have been defined to generate effective building with nature solutions (de Vriend and van Koningsveld, 2012).

1. Understand the system (including ecosystem services, values and interests).
2. Identify realistic alternatives that use and/or provide ecosystem services.
3. Evaluate the qualities of each alternative and preselect an integral solution.
4. Fine-tune the selected solution (practical restrictions and the governance context).
5. Prepare the solution for implementation in the next project phase.

Despite the gained traction, effective tools are yet to be realized which concretely compare and analyse the efficacy of nature-based solutions. Due to the complex and multi-actor nature of the approach, the resulting impact of nature-based solutions can be hard to quantify for every stakeholder (de Vriend et al., 2014).

A.2 Frame of Reference Approach

The frame of reference approach was developed to bridge the gap between coastal science and coastal policy management. This objective approach aims to match specialist knowledge with end user needs by making the essential decision-making components explicit (van Koningsveld, 2003; van Koningsveld and Mulder, 2004). Figure 2.1 describes the components that make up the FoR framework.

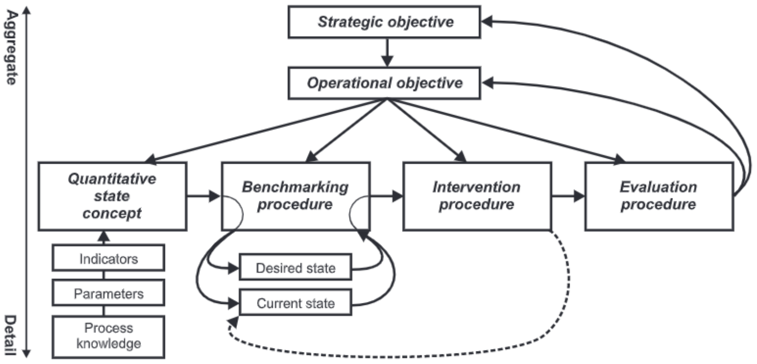


Figure 2.1: *The ‘Basic’ FoR (van Koningsveld, 2003)*

The strategic objective can be seen as the overarching goal of the infrastructure intervention within the natural and socio-economic contexts. All stakeholders contribute towards this vision. Each stakeholder then has its own operational objective which ''further defines how the natural system interacts with the socio-economic context'' (Iglesias, 2022).

The following operational steps (Quantitative State Concept, Benchmarking procedure and Intervention procedure) describe what the current state of the system is, how changes in the system can be evaluated, and the impact of an intervention on the system respectively. Finally the Evaluation step consists of checking if each stakeholders operational objective has been met, and then if these separate outcomes contribute towards the overall strategic objective (Iglesias, 2022).

In the context of assessing port logistics and freshwater supply, two individual operational objectives are to be met whilst satisfying one overall strategic objective. Figure 2.2 illustrates the approach for multiple stakeholders.

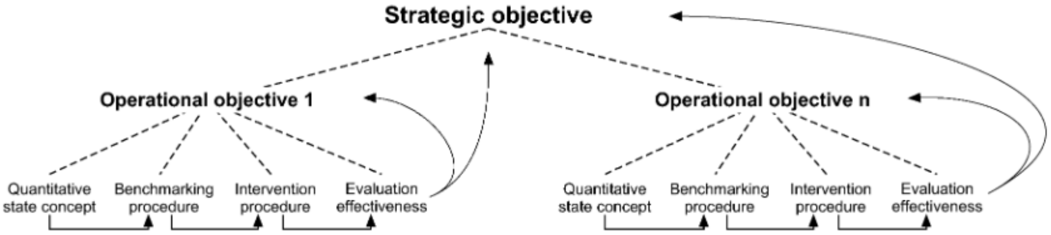


Figure 2.2: *The FoA approach for multiple stakeholders (van Koningsveld, 2003)*

A.3 Salinity Profiles and Estuary Classes

Salt transport is a result of the interaction between salt and freshwater in estuarine environments. The difference in density between salt (higher density) and freshwater (lower density) causes hydrodynamic interactions to take place within the estuary, resulting in the transport of salt water.

Estuaries can be classified in many ways, yet the most relevant in this research is according to salinity structure. The structures are determined by the relative dominance of stratification over vertical mixing, with salt wedge exhibiting the largest dominance, followed by (highly) stratified, partially stratified and lastly well-mixed. The orientation of the salinity gradient changes according to the level of stratification. The salt wedge case showcases a vertical salinity gradient, whereas the well mixed situation exhibits a horizontal gradient (Iglesias, 2022).

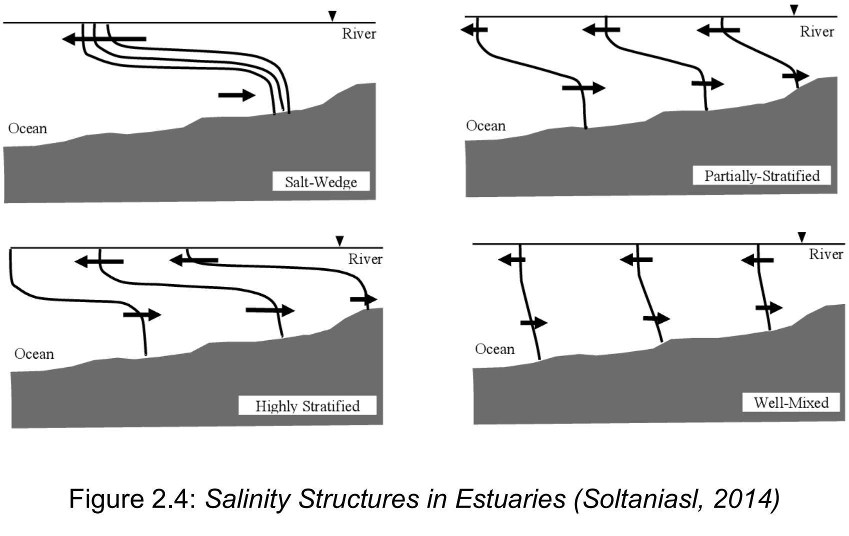
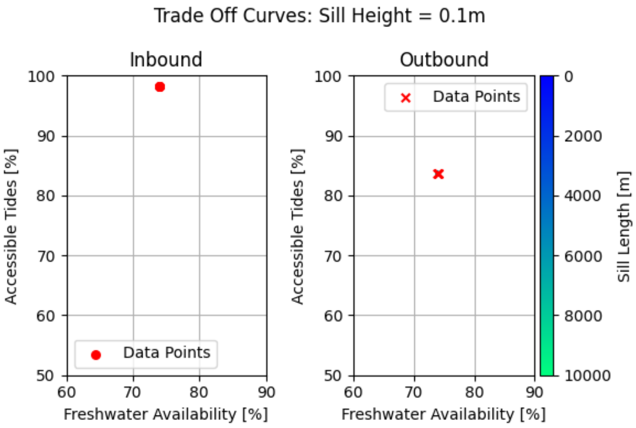
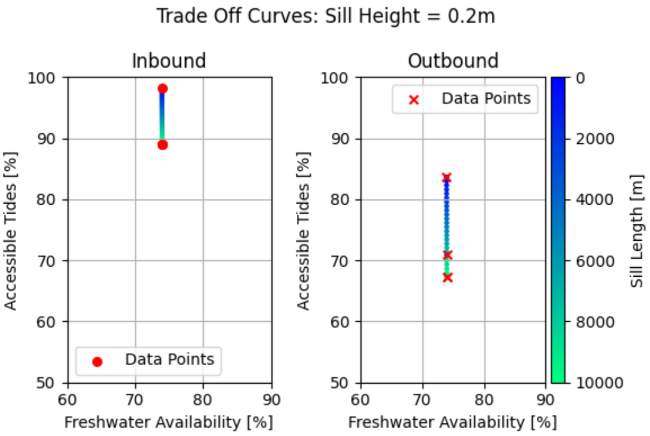


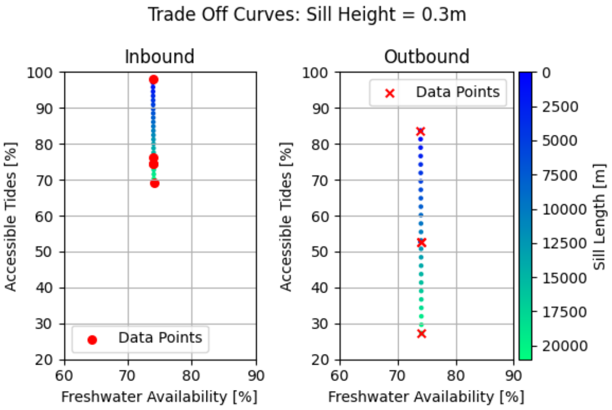
Figure 2.4: *Salinity Structures in Estuaries (Soltaniasl, 2014)*

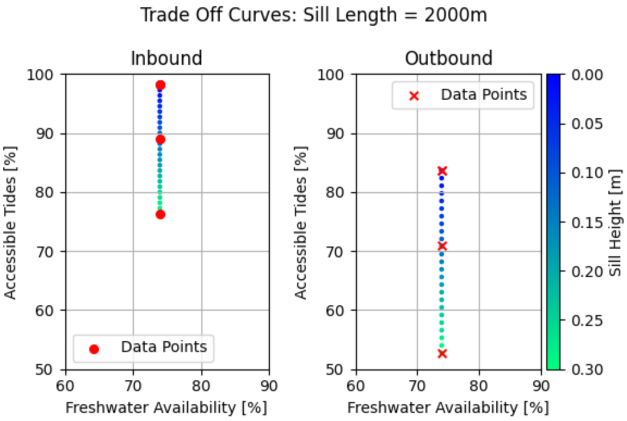
When river discharge is relatively large in comparison to tidal forcing an estuary can generally be classified as stratified. Conversely when discharge is small compared to tidal forcing, the well mixed type often applies as a basic indication. (Iglesias, 2022).

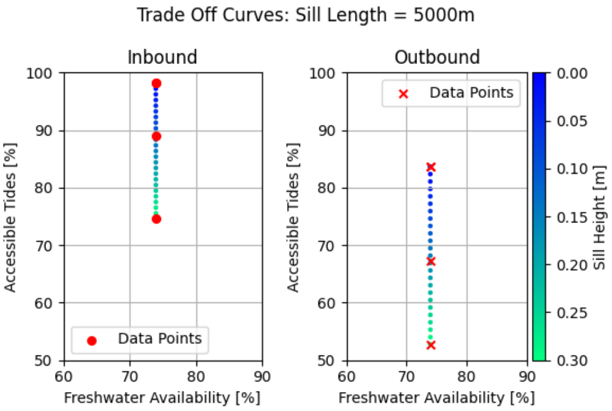
Appendix B: Trade Off Curves for Sill Designs

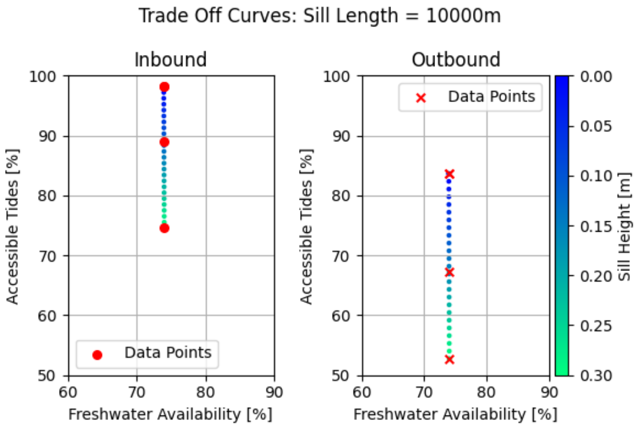


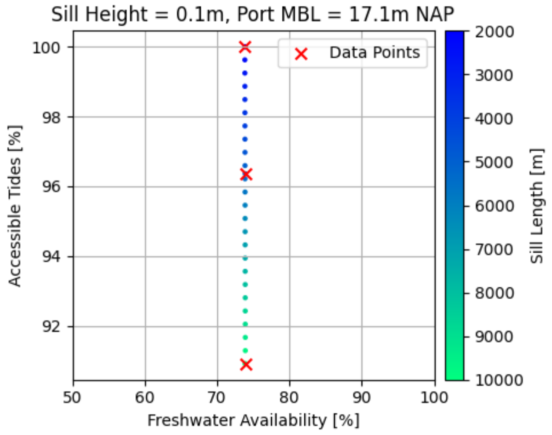








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94
92
Freshwater Availability [%]
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80
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Sill Length [m]
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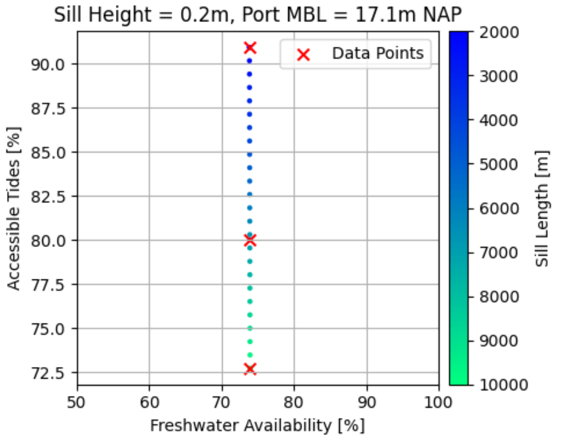
4000
5000
6000
7000
8000
9000
10000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85.0
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77.5
75.0
72.5
Freshwater Availability [%]
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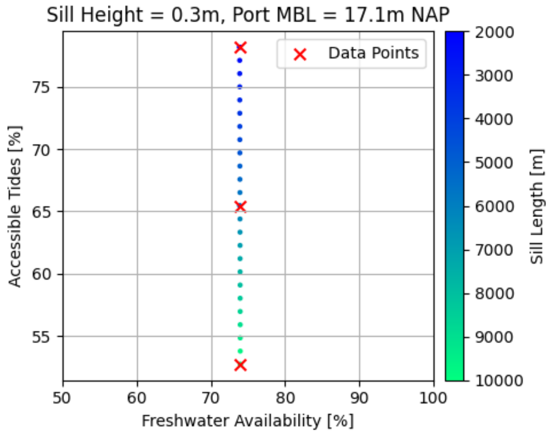
70
80
90
100
Sill Length [m]
2000
3000
4000
5000
6000
7000
8000
9000
10000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Freshwater Availability [%]
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Sill Length [m]
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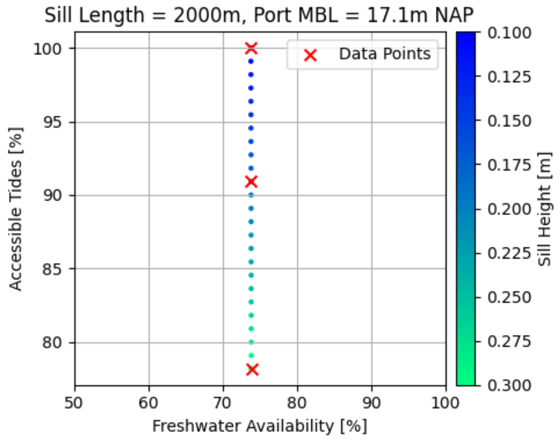
9000
10000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85
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Freshwater Availability [%]
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60
70
80
90
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Sill Height [m]
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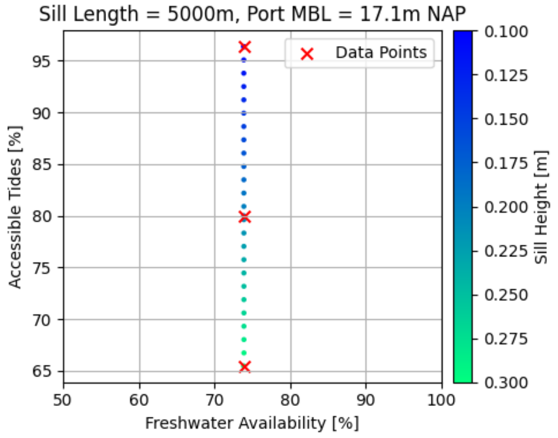
0.150
0.175
0.200
0.225
0.250
0.275
0.300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Freshwater Availability [%]
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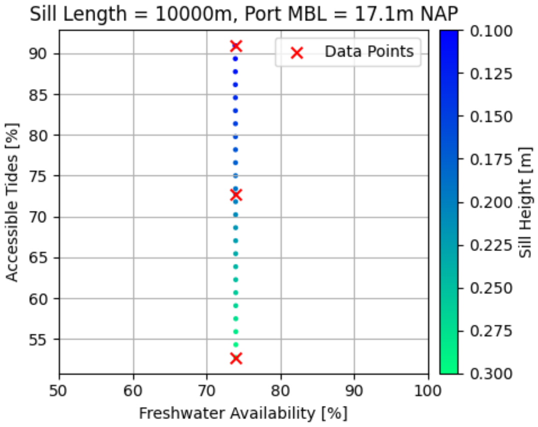
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Freshwater Availability [%]
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70
80
90
100
Sill Height [m]
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0.150
0.175
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0.225
0.250
0.275
0.300