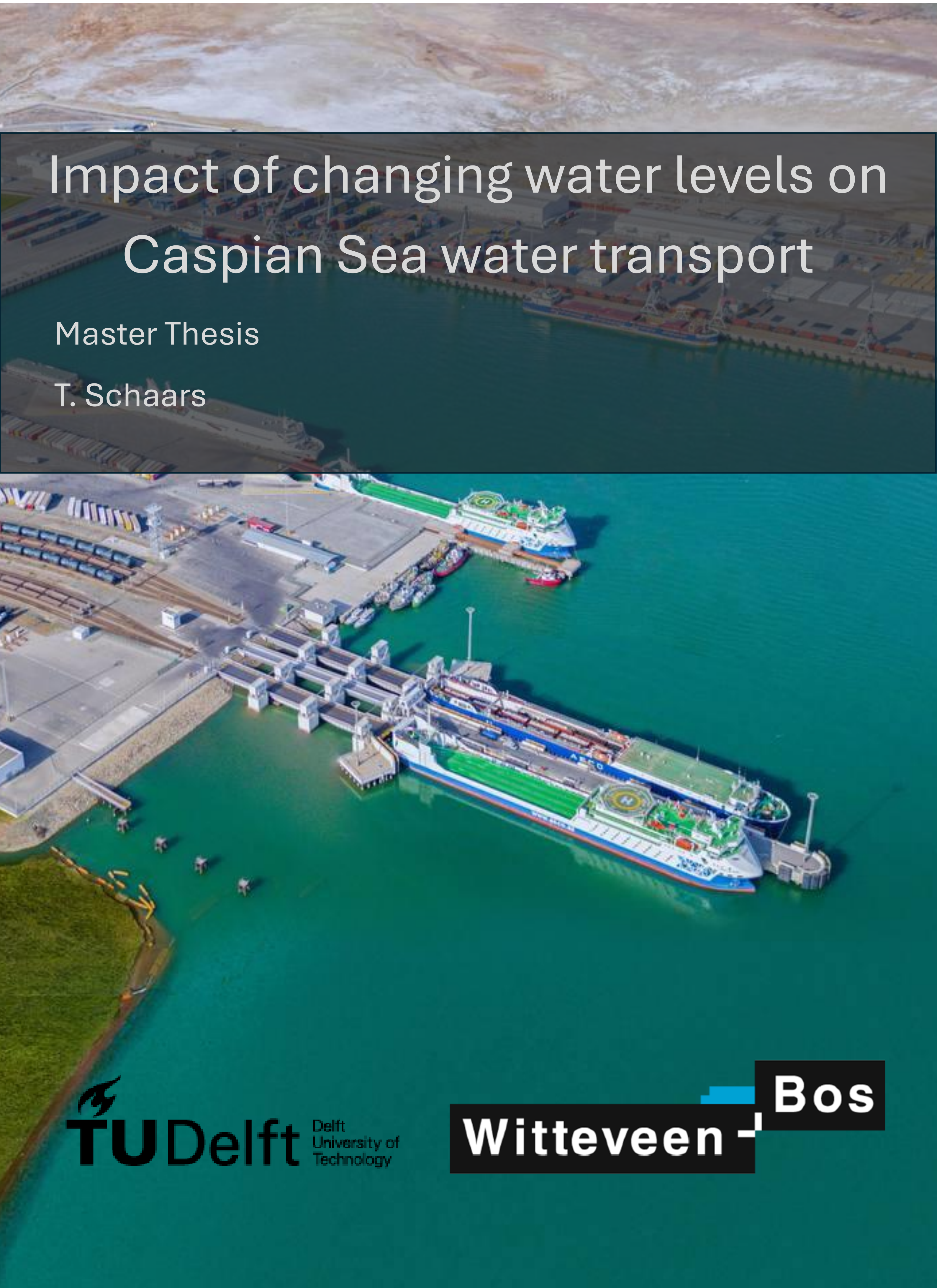
# Impact of changing water levels on Caspian Sea water transport

Master Thesis

T. Schaars



# Impact of changing water levels on Caspian Sea water transport

by

## T. Schaars

To obtain the degree of Master of Science

at the Delft University of Technology

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Cover: aerial view of the Port of Baku

# Preface

The following document represents the findings of the master's thesis conducted in order to fulfil the requirements of the Hydraulic Engineering programme at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. This research was done in collaboration with the Delft University of Technology and Witteveen + Bos. My motivation for taking on this thesis can be traced back to my interest in port & waterway interactions, especially the logistics of the traffic. Combining this with my affinity for python programming, made this a suitable thesis topic.

I would like to thank Witteveen + Bos for offering me the opportunity to work on my thesis at their company and for their guidance during the process.
Next, I would like to take this opportunity to thank the people that have supervised me during this thesis. Firstly, I would like to thank Mark van Koningsveld, the chair of my committee, for his useful insight into what a Master Thesis is supposed to be and for all the feedback during our meetings. I would also like to thank Christiaan Loeber for the weekly supervision and helping out with problems that arose each week. Next, I would like to thank Lex de Boom for suggesting this topic to me and setting up the thesis, combined with the feedback during our meetings. Finally, I would like to thank Femke Vossepoel for her view on this thesis from outside of the hydraulic engineering department. This helped a lot with creating future water level scenarios and getting a well-structured report.

*T. Schaars*

*Schoonhoven, October 2025*

# Abstract

Declining water levels driven by climate change increasingly threaten the efficiency of maritime transport systems. This thesis develops a transferable methodology to quantify how such changes affect port-to-port waterborne transport. The framework integrates physical, operational, and infrastructural aspects to assess how throughput capacity evolves under varying water depths.

The method consists of three components. First, navigational depth related bottlenecks are identified by subdividing a route into port basins, access channels, and an open sea section, using bathymetric and infrastructure data to locate depth-critical areas. Second, a discrete-event simulation model built in the open-source package OpenCLSim represents vessel operations, handling cycles, and sailing behaviour under different water levels. Third, a one-at-a-time sensitivity analysis uses this simulation to systematically vary parameters. Fleet size, number of berths, (un)loading speed and the minimum percentage a vessel must be loaded to sail, are varied to quantify their influence on transport volumes as water levels fall.

The methodology is applied to Caspian Sea routes between the Port of Alat (Azerbaijan) and the Kazakh ports of Aktau and Kuryk. A depth-related navigational bottleneck occurs in the access channel of the Alat port. Simulation results show that between 2027 and 2033 transport volumes drop to 50% on this route if no changes are made. The number of vessels in the fleet becomes increasingly important as water levels fall.

This structured framework enables shipping companies and policymakers to anticipate and mitigate performance losses in port-to-port water transport systems under future low-water scenarios.

# Executive Summary

Global climate change is affecting waterborne transport routes in different ways. In some places water levels keep rising. In the Caspian Sea, water levels fall due to climate change. This causes issues for waterborne transport routes. At low water levels, the depth of a vessel can be restrictive. As time goes on and water levels keep falling, more problems on conventional sailing routes on the Caspian Sea will occur. The goal is to determine at which location along a water transport route, depth becomes restrictive, but also which other parameters become more important when the navigable depth decreases.

This thesis develops a new methodology to assess how waterborne supply chains respond to changing water levels. The approach combines navigational bottleneck identification with simulation modelling using the open-source package OpenCLSim. It integrates bathymetric data, fleet composition, port infrastructure, seasonal effects, and handling times to estimate route throughput capacity under future water level conditions. A one-at-a-time sensitivity analysis was applied to determine which parameters are most critical under both current and reduced water levels. This way it will be possible to both predict when water transport becomes impossible, and what changes in infrastructure can potentially be made to increase transport volumes under changing water levels.

Applied to the Caspian Sea, the method demonstrates its value in linking physical environmental change directly to transport performance. The case study focused on the routes between the Port of Alat in Azerbaijan and the Kazakh ports of Aktau and Kuryk, using three cargo types: general cargo, liquid bulk, and containers. Water level data of the Caspian Sea was collected to determine the influence of seasonal changes on water levels. A literature review showed that the general consensus is that the water levels will keep on falling, depending on the amount of water that is extracted from the Caspian Sea and the human influence on climate change. This literature review and the seasonal effects helped generate potential future water level scenarios.

For the navigational bottleneck, the route was divided into separate sections that potentially can be a bottleneck under the influence of climate change. These sections are the port areas, the access channels and the open sea stretch. Qualitative research showed that the ports are regularly dredged and therefore not a risk of being a bottleneck. The open sea stretch turned out to be sufficiently deep, so not bottleneck was expected here. The access channels in the Kazakh ports of Aktau and Kuryk both increased in depth to more than 10 meters quickly outside of the port area and were therefore not bottlenecks. The access channel of the port of Alat does not pass three meters depth in its first kilometres and therefore is the shallowest point and the depth related bottleneck when water levels keep decreasing.

Relevant data was collected to be able to run the simulation. A base case was created that represents the true situation on the route as accurately as possible for all three cargo types. This base case then was run different scenarios where the average water level decreases with 0.2 meters each time. This helped determine at which water level the transport capacity drops the most. It turns out that a water level drop between 2 and 2.5 meters decreases the transport capacity to 50% for all three cargo types. Coupling this to the created future water level scenarios, the prediction can be made that the tanker category carrying liquid bulk will decrease its capacity to 50% somewhere between 2027 and 2031. For the passenger ferries carrying the containers and the general cargo vessels, this 50% decrease happens between 2028 and 2033 according to the simulation.

A sensitivity analysis focussed on separate cargo types helped determine how changes in the base case impact the transport capacity. The one-at-a-time variation varied the following parameters: Number of berths, minimum loading percentage, seasonal effects, (un)loading speed and the number of vessels in the fleet. These variations are done for all water levels, so heatmaps are created for each combination of varying parameter and the water level. The general cargo transport showed that the terminal capacity was restricting the transport capacity in the base case. For the passenger and tankers, the restrictive factor was the fleet size.

A best- and worst-case scenario was made for each varying parameter. Comparing the transport capacities for these scenarios at multiple water levels showed which parameters become more important as water levels fall. It turns out that for general cargo at low water levels the terminal capacity is no longer restrictive. So, a larger fleet will be effective at lower water levels but not at higher water levels.

Based on the findings, the study recommends operational and infrastructural measures. An operational measure that is encouraged are decreasing minimum loading percentage. Infrastructural measures include targeted dredging, add an extra berth for general cargo and most importantly increase the fleet. For the Caspian region specifically, transport capacity can be reduced to fifty percent between two to eight years. Therefore, timely investment in infrastructure and better regional coordination between Azerbaijan and Kazakhstan is essential to maintain future transport reliability. The thesis concludes that if no action is taken, the continued fall of Caspian Sea level will result in inoperable maritime routes.

By providing both a transferable method and case-specific insights, the thesis shows that declining water levels can rapidly decrease a systems transport capacity. The framework offers a practical tool for ports and policymakers to anticipate risks that occur when a water transport route becomes shallower. It shows that parameters that are important at current water levels may become less important at lower water levels and vice versa.

## Contents

# 1. Introduction

## 1.1 Context

Kazakhstan and Azerbaijan are keen to maintain and expand the capacity of their shared shipping routes. These routes are crucial for facilitating trade between China and Europe. While the primary trade route between these regions is marine shipping, alternative routes are gaining attention. One such alternative is the middle corridor, a less familiar but strategically significant route that traverses Kazakhstan, the Caspian Sea, and Azerbaijan before reaching the Black Sea and beyond.

The middle corridor involves goods being transported from China via rail to Kazakhstan, followed by water transport across the Caspian Sea to Azerbaijan (Guliyev, 2023). From there, goods can proceed to Georgia and the Black Sea or travel by rail to Turkey. This route has seen a 63% increase in trade volume in 2024 since the start of the Russia-Ukraine conflict (Abbasova & Allison, Can the Middle Corridor be Europe's Middle Ground?, 2025). Although the middle corridor is currently dominated by Kazakhstan's exports, its potential for increased cargo traffic from China to the EU, positions it as a viable alternative to the northern and maritime routes. This is shown in Figure 1.

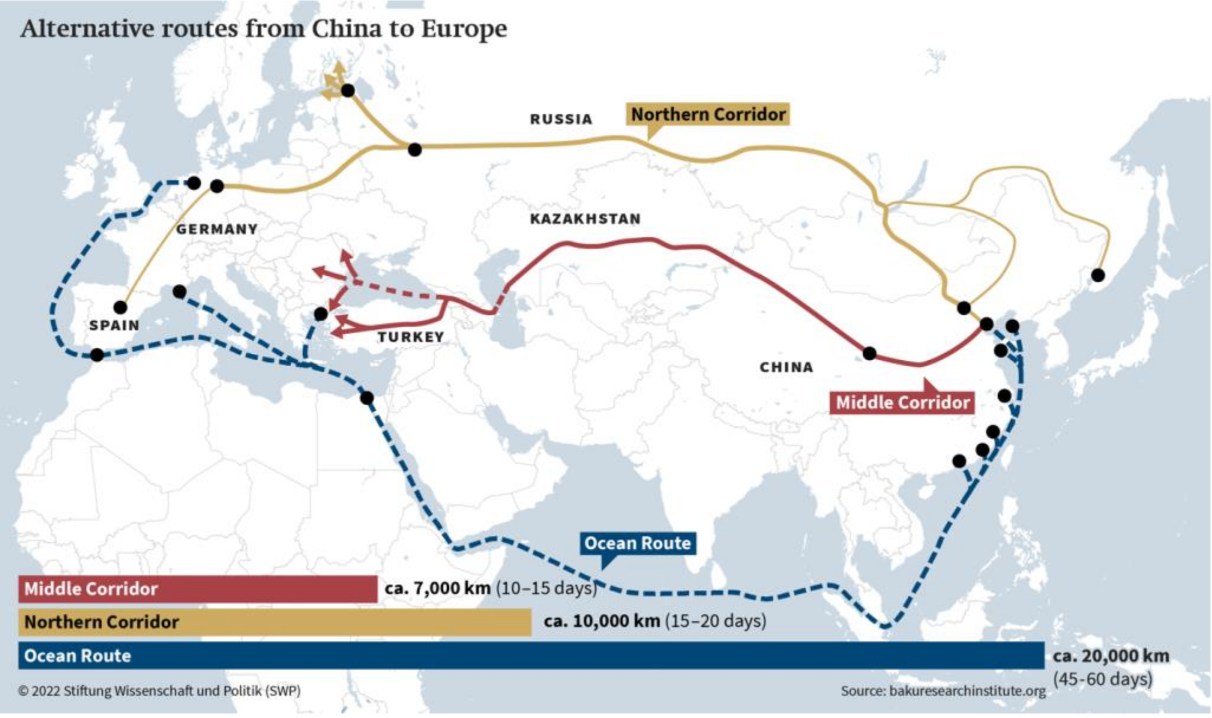


*Figure 1: Map showing three main transport routes between China and the EU (Guliyev, 2023).*

Despite its potential, the middle corridor faces significant challenges. It is more expensive and time-consuming than the northern route, primarily due to high tariffs and lengthy delays at ports and railway stations. However, reducing costs and travel time could make it a competitive option. Sanctions on Russia have increased transport costs along the northern corridor, and the travel distance and time is higher than the middle corridor.

The ocean route also faces many challenges, it has longer travel times and depends on sailing through the Suez Canal and the Red Sea. Safe and efficient passage on this route is not guaranteed anymore since tensions are rising in the Middle- East. Houthi attacks on vessels sailing the Red Sea between the end of 2023 and the beginning of 2025 caused major disruptions for transport along the sea (Helwa & Al-Riffai, 2025). Although these attacks have ended, there is no guarantee that something similar does not happen. An advantage of the middle corridor route is that is passes fewer countries than the other two corridors. The only countries between China and the EU for the middle corridor are Kazakhstan, Azerbaijan and Georgia. This can be seen in Figure 2.

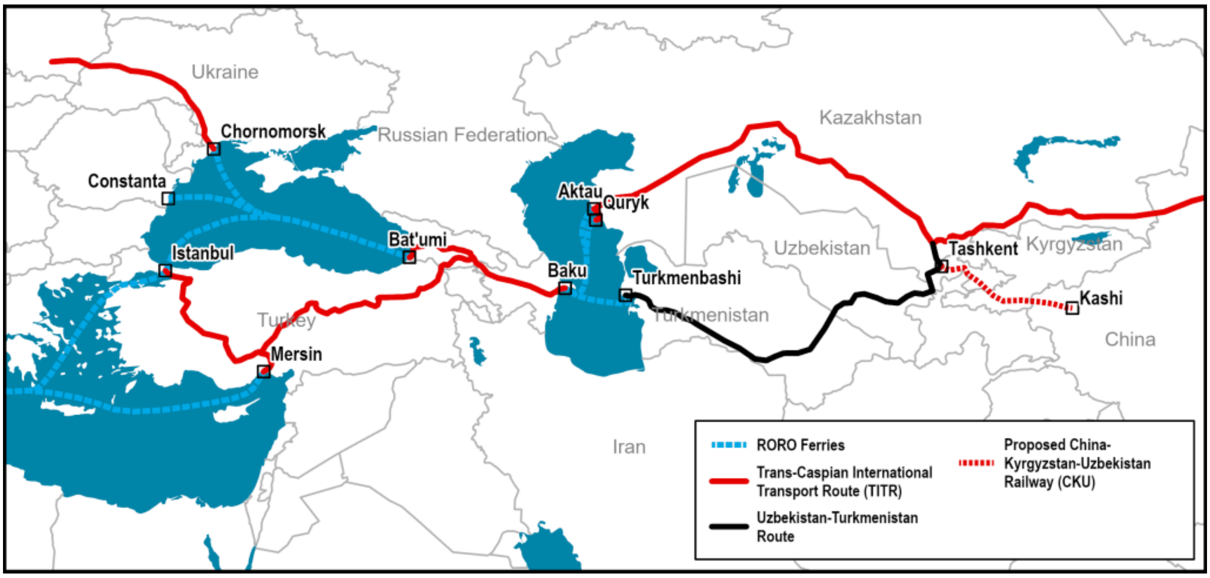


*Figure 2: Map of routes over the middle corridor (Notteboom, Pallis, & Rodrigue, Train Ferries on the Caspian Sea as Part of the Middle Corridor, 2022).*

## 1.2 Problem statement

Countries around the Caspian Sea stand to benefit from increased transport across the sea, as it stimulates economic activity, generates jobs, and attracts businesses. However, a significant challenge rises: the fluctuating water levels of the Caspian Sea. Over the past decade, the Caspian Sea level (CSL) has dropped by more than one meter, a trend which is expected to continue (Koriche, Singarayer, & Hannah L Cloke, 2021). Predictions suggest a potential CSL drop of over nine meters within the next century. Historical data also shows significant variability, with swings of around three meters occurring in the last decade alone. This variability creates uncertainty for maritime infrastructure, since low water levels may lower the reachability of ports.

Both Kazakhstan and Azerbaijan are upgrading their ports to handle greater throughput, but these designs might overlook the implications of future CSL changes. If water levels fluctuate drastically, the ports may struggle to function effectively.

This thesis aims to address this issue by exploring how the maritime route between Aktau/Kuryk (Kazakhstan) and Baku/Alat (Azerbaijan) can sustain its current transport volumes under varying future water levels. It will also determine what parameters influence transport capacity the most. By examining these factors, the research will contribute to securing the long-term viability and growth of the middle corridor.

## 1.3 Research gap and objective

A model has been developed  to create a discrete-event model to measure the performance of channel depth by measuring waiting times (Bakker, et al., 2024). The model uses Automatic Identification System (AIS) and hydrodynamic data as its main input. The model is validated by hindcasting one year of a terminal in the Port of Rotterdam. This model gives great insight into mesoscopic scale port interactions. However, the research is limited to the performance of one port and measured in waiting times.

A second report suggests a method to explicitly include the cascading effects of low discharge events on river transport (Vinke, et al., 2022). It converts the low discharges to the low water depths and simulates water transport for these low depths using the 'OpenCLSim' python package. The model identifies changes in number of trips, transported volume and costs. The goal of the research is to look beyond depth-bottlenecks and see how lower discharge causes other issues in the supply chain.

Both methods are examples of good ways to identify arising issues at lower water depths. There seems to be no single method that reviews the total transported volumes of a full port to port transport system. Therefore, the goal of this thesis is to create a macroscopic method which builds on the previous research and determines performance of shipping routes from port to port, by quantifying transported volume. The method will focus on identifying bottlenecks that may arise in future water level scenarios. These scenarios are obtained by reviewing historical water levels and 'Earth system model' predictions. A distinction will be made between navigational bottlenecks and other potential bottlenecks as a cause of lower water levels.

## 1.4 Research questions and structure

The research gap and objective lead to the following research question:

> **How do waterborne supply chains react to changing water levels with an application to the Caspian Sea?**

The main research question is accompanied by the following sub-questions:

1. **What are the physical and ship related factors that influence water transport performance?**
2. **How to locate potential bottlenecks due to changing water levels in a waterborne supply chain?**
3. **What is the current performance of water transport, measured in total cargo volumes, in the Caspian Sea and how will it likely be affected by future sea level scenarios?**
4. **What are possible solutions for water transport where water levels are expected to fall, applied to the Caspian Sea?**

## 1.5 Research scope and approach

This research is limited to developing a method for identifying potential bottlenecks between the berths of two ports. Aspects such as hinterland connectivity and storage capacity within ports are excluded from the analysis. Once a vessel has completed unloading its cargo, the cargo falls outside the scope of the study. Transshipment operations and the development of new port locations are also not considered.

The analysis assumes two existing ports, which may vary in the number of available berths and unloading speeds. While safety regulations and policy frameworks are recognised as influential factors in waterborne transport, they are beyond the scope of this research. The focus is restricted to assessing potential total transport capacity between ports.

Future water level scenarios will be derived through a combination of literature review and data extrapolation. These scenarios are not intended to represent precise predictions but rather to provide a broad understanding of possible futures based on varying degrees of human influence on climate change.

To identify potential navigational bottlenecks, route depths will be assessed. It is assumed that port regions will continue to be dredged adequately as water levels decline.

Given that vessel types vary in cargo compatibility and berth requirements, the analysis will focus on a single cargo type, under the assumption that all vessels can carry any available cargo of that type. Multifunctional vessels that can carry more than one cargo type are not considered.

The method will be applied on a case study on the Caspian Sea, specifically analysing the route between the port of Baku and the ports of Kuryk and Aktau for three different cargo types.

## 1.6 Readers guide

Chapter 1 introduces the problem and objectives, providing the foundation for the study. In Chapter 2 a literature review will be done. Current research will be reviewed and sub-question 1 can be answered. Chapter 3 will be about the method and materials. Here the method to identify bottlenecks will be explained and all available Caspian Sea case data will be introduced. This will help answer sub-questions 2 and 3. Finally, Chapter 4 will show the results of the newly created method applied on the Caspian Sea case. This will help answer sub-question 4. In Chapter 5, a discussion, conclusions and recommendations will be made.

# 2. Literature review

This chapter presents the literature study and contributes to a deeper understanding of water transport systems. The chapter is divided into four sections. The first section will introduce water transport systems and state what is important. Next the current state of the art literature is reviewed, which will help determine what extra research is required. Finally, the physical and ship related factors that influence water transport will be discussed. This will help answer sub-question 1:

*What are the physical and ship related factors that influence water transport performance?*

## 2.1 Principle of water transport

There are many physical factors that influence the performance of a water transport system. The importance and adjustability of these factors are explained and explored individually. Vessels can encounter several things on their route from port to port. Assuming the vessel starts empty on the water near a port. The vessel has to sail through an access channel into the port. Here it manoeuvres to be in line with the berth. The vessel sails slowly to the berth and will be moored. When the vessel is secured, the loading phase can begin. Depending on the cargo type, the cargo will be loaded by cranes, pipeline or conveyor belts.

When the cargo is loaded, the vessel unmoors, manoeuvres and finally sails away from the port through the access channel. From here the vessel may sail over a combination of rivers, lakes and seas. At the destination port, the access channel, manoeuvring and mooring procedure is repeated. Here the vessel is unloaded, and it can unmoor and sail away empty, or be loaded with different cargo.

A fully loaded vessel has a larger draught than an unloaded vessel. The water depth available therefore influences how fully a vessel can be loaded. This water depth is built up of many different factors. To ensure vessels can keep on sailing a minimum Under Keel Clearance (UKC) is given by the port authorities.

Water depth and all factors that will be mentioned further on, are only affecting transport capacity if the depth is close to the vessel draught. Therefore, one of the first points of action is to review the water depth and bathymetry along a route. Then variability in water depth for the low depth locations must be determined. This usually occurs near the ports or on rivers.

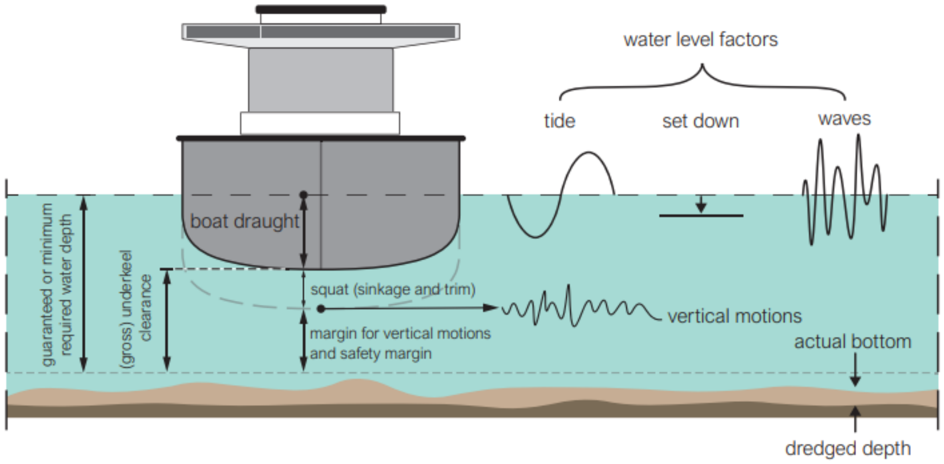


*Figure 3: Schematic display of UKC (Koningsveld, Verheij, Taneja, & Vriend, 2023)*

Since transport volumes is the focus of this research, factors that influence safety are omitted. Only factors that influence transport capacity, such as available depth, are considered. Table 1 shows a schematic overview of the parameters that are deemed significant factors influencing water transport volumes.

Section 2.3 will elaborate on the Physical factors and section 2.4 will elaborate on the vessel- and fleet related factors

| Physical factors | Vessel- and fleet related factors |
|---|---|
| Base water level | Vessel draught |
| Tide | Fleet composition |
| Waves | Berth availability |
| Seasonality | Vessel capacity |
| Wind set-up / set-down | Congestion |
| Bed level | Policy |

*Table 1: Schematic overview of research parameters*

## 2.2 State of the art methods

As stated in 1.5 there is a study that reviewed the influence of low water depth on the interactions in a port system (Bakker, et al., 2024). It focuses on the effects on waiting times in one single port. The study quantifies performance of access channel depth by studying waiting times for a representative fleet. It uses a python simulation based on the 'OpenTNSim' package.

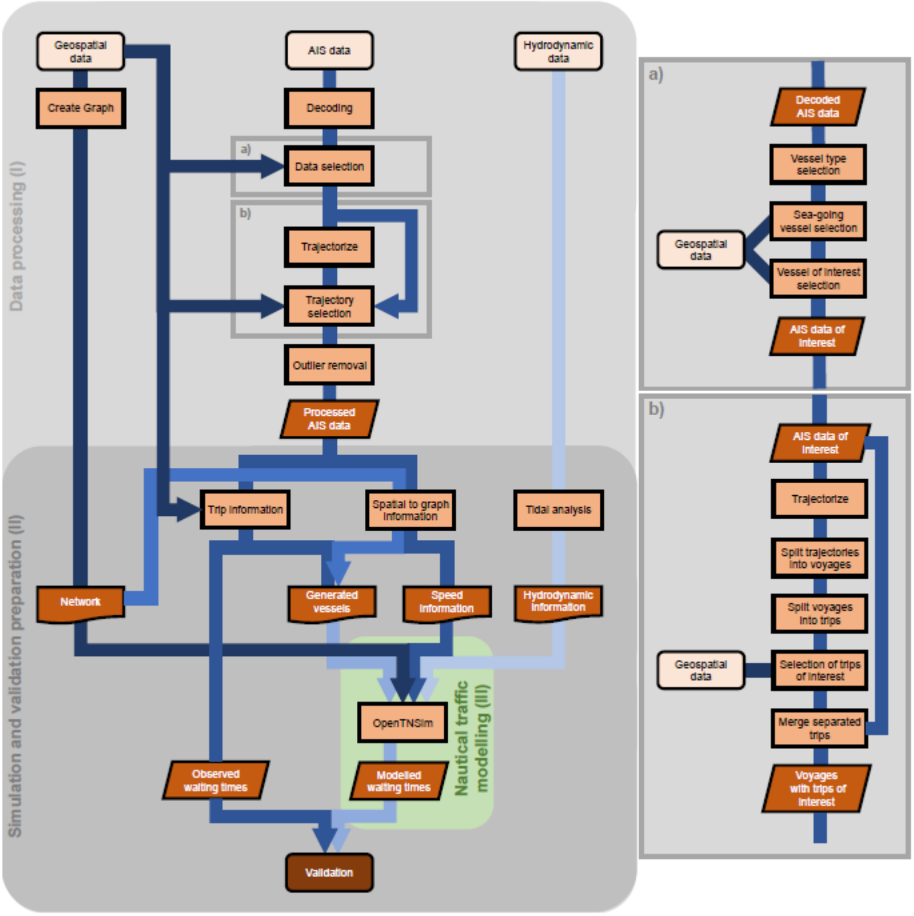


*Figure 4: Information flows for the set-up and validation of the nautical traffic model, consisting of data processing (I), simulation and validation preparation (II), and nautical traffic modelling (III). (Bakker, et al., 2024)*

Figure 4 shows the flow chart for that research. This approach will be modified to fit the requirements of this thesis, but the main idea will be similar. For example, this research will use the 'OpenCLSim' package instead of 'OpenTNSim'. This is because 'OpenTNSim' is focused on vessels moving over a determined network, whereas 'OpenCLSim' has the option to determine which cycles the vessels operate in (Koningsveld & Baart, OpenTNSim).

The work of Vinke focuses on creating a model to understand risks and effect of sustained low water levels for Inland Waterway Transport of (Vinke, et al., 2022). The water level is determined by calculating water depths using a 1d flow solver called SOBEK (Deltares, 2019). This software is used to calculate the water depth from known river discharges. The method is similar to what is required in this thesis, but it is specified for Inland Water Transport only, whereas the goal in this research is to get a general approach for all kinds of water transport. The research uses OpenCLSim which is what is going to be used in a similar way in this thesis.

Both these studies are a useful beginning point for this thesis to build on. The goal is to use these existing methods as a basis for a more generalized method, which will help determine important parameters in a water transport supply chain.

## 2.3 Physical factors

Section 2.1 showed what generally is important in a water transport system. This section will expand on that and dive deeper into how each specific physical factor affects water transport performance, which will be measured in transported volumes.

**Water level**

The water level is an important factor influencing water transport capacity. Vessels require a certain depth of water to be able to sail fully loaded. There are many factors that can influence water levels on a route. Their importance differs per route. Water level is based on the factors listed below (Douglass & Krolak, 2008):

*Base water level*
The base water level represents the long-term average level of a water body under undisturbed conditions. It is determined by the natural balance between inflows (river discharge and rainfall) and outflows (evaporation and water extraction). Climate change may influence the inflows and outflows resulting in a changing base water level.

Since the research is also focused on future transport volumes, future base water levels are important. Predictions of future water levels will be made by reviewing case specific literature.

*Tide*
Tides are periodic fluctuations in water levels driven by gravitational forces, mainly from the moon, and to lesser extent from the sun (Parker, 2018). These gravitational pulls create predictable high and low tides, usually twice per day in many coastal areas. These high and low tides can have amplitudes of several metres in coastal areas, resulting in a significant impact on the water level. Lakes and the more inland part of rivers are less influenced by tide, up to a point where it is only several centimetres. Tides on open seas are usually not important because there is a sufficient water depth.

*Waves*

Waves can be caused by vessels or wind among other things. Waves cause a temporary increase and decrease in water level. This can cause a vessel bottom to get closer to the bed level, these wave conditions are assumed to fall within the safety margin that is UKC and are therefore not considered further.

*Seasonality*

Seasonality describes the regular, predictable changes in water levels that occur due to variations in climate throughout the year. Factors such as rainfall, temperature and evaporation rates have significant impact on water levels (Antão - Geraldes & Boavida, 2005). It is common that after winter, snow and ice melting in the spring can cause an increase in water level. A warmer summer may increase evaporation rates and decrease water levels again. Recognizing these seasonal trends is important for long-term water management, ensuring that navigational channels and port basins may be affected for longer periods of time.

*Wind set-up / set-down*

Wind set-up is the temporary elevation of water levels caused by the sustained force of wind pushing water toward a shore (Drews & Han, 2010). A steady wind can create a significant set-up or set-down which is mainly seen in lakes, but also in other water bodies. This effect can lead to short-term water level changes, which can cause issues at low depths if these are not taken into account. Set-up at one side of a lake usually means there is set-down on the other side of this lake.

*Bed level*

The available depth depends on the bottom material expected on the route. Harder material requires more distance from the vessel bottom, while the softer material is more forgiving and requires less distance. When there is soft mud as a bed, vessels may sail through the mud with the bottom of the vessel being lower than the bed level (Vantorre, 2008) (Wilson, Sons, 2022).

## 2.4 Ship related factors

The previous section discussed physical factors that influenced the available water depth. In this section other important ship related factors are discussed. These have effect on transport capacity in other ways.

***Vessel draught***

The most important factor determining vessel draught is its design. Each vessel has its own empty draught and fully loaded draught. This varies for each design and vessel type.

The expected hull design of vessels varies depending on whether they operate in seas, lakes, or rivers (Ghosh, 2022):

- Sea Vessels: Ocean-going ships typically have deep V-shaped hulls designed for stability in open waters, where waves and strong currents are common. These hulls provide better hydrodynamics, reducing drag and improving fuel efficiency for long-distance travel. These often have a high draught.
- Lake Vessels: On large lakes, vessels often feature a semi-V hull or a moderate draught to balance stability and fuel efficiency while remaining adaptable to varying water levels. Since waves are smaller than in open seas, these vessels do not require as deep a hull as ocean-going ships.
- River Vessels: River transport typically relies on flat-bottomed or shallow-draught vessels, such as barges, which are optimised for navigating narrow, shallow, and slow-moving waters. Their design allows them to carry large loads while avoiding excessive draught that could cause grounding.

***Fleet composition***

The available fleet on a route is one of the most important pieces of data to have. Each vessel has a different: Capacity, draught, length, width, and dedicated cargo type. Examples of different dedicated cargo type vessels are (Sinay Maritime Data Solution, 2022):

- Container vessels
- Chemical Tankers
- Bulk cargo carriers
- Crude oil Tankers
- Liquefied Natural Gas (LNG) Tankers
- Ro-Ro vessels
- General Cargo vessels

Ro-Ro vessels are Roll on – Roll off vessels. Here cars, trucks or trains can drive onto the vessel and drive off it. This includes ferries. Vessels are usually not suited to carry any other cargo type than its dedicated cargo type. An exception is the ‘General cargo vessel’. This one can carry containers as well. The Chemical- Crude oil and LNG tankers can be grouped as liquid bulk tankers.

Knowing all the previously mentioned fleet properties, will help get an estimate on trip duration per vessels. Combining this with the vessel’s capacity will result in an estimate of transport capacity.

### ***Berth availability***

The number of berths in both the origin- and the destination ports are important factors for transport capacity. This determines how many vessels can be (un)loaded at the same time. Tankers can be (un)loaded at jetties instead of a quay wall. This type of berth is only accessible for tankers. This is shown in Figure 5.

*Figure 5: A view of unloading an oil tanker (RiverLake, sd)*

Ro-Ro vessels can be (un)loaded perpendicular to the shore as shown in Figure 6. Here the vehicle can drive off and no cranes or port equipment are required.

*Figure 6: A view of unloading a Ro-Ro Vessel (Mandra, 2020)*

The other dry bulk, general cargo and container vessels are unloaded using cranes that are either onshore or on the vessel itself as seen in Figure 7. These moor alongside the shore, so require more space than Ro-Ro vessels and tankers.

*Figure 7: A view of unloading general cargo vessels (Adobe Stock , sd)*

Seeing how different cargo types (un)load shows how each require different berths. This is why ports have dedicated terminals for the type of vessels that are expected. Knowing the number of berths, and which cargo type they serve is therefore an important factor to determine transport capacity.

### *Vessel capacity*

The total capacity of each vessel is reported to know how much can be transported. When water levels are high enough, the full capacity can be utilized. When water levels are low, no transport is possible. Assuming that the weights of cargo units loaded on a vessel are the same, it will be assumed that the relation for the intermediate vessel draught is linear. So, the transport capacity when the draught is between the full and empty draught becomes:

$$Capacity = Total\ capacity * \frac{Safe\ Water\ Depth - Draught\ empty}{Draught\ Full - Draught\ empty}$$

For example, if the total capacity of a vessel is 1000, with an empty and full draught of 3 and 5 meters respectively. A safe water depth (accounting for UKC) of 4 meters will result in a capacity of $C = 1000 * \frac{4-3}{5-3} = 500\ which\ is\ 50\%$. This will allow vessels to sail with less load if water levels keep falling.

### *Congestion*

(Bakker, et al., 2024) differentiates downtime and congestion. Downtime is when vessels are unable to sail due to issues that are not related to other vessels. The main one being a low water level. Other downtime causes can be lack of daylight or working hours on the terminal. Congestion occurs due to other vessels being in the port as well. Berths may not be available, the access channel or turning basing can be occupied, or all tugboats are already in use for other vessels. Downtime and congestion cause delays, which effects can cascade into longer delays.

Congestion in waterways, ports, and access channels can significantly impact the efficiency of water transport. High traffic density leads to delays, increased waiting times, and reduced overall transport capacity. This issue is particularly relevant in transport hubs where multiple vessels arrive and depart within a limited timeframe (Koningsveld, Verheij, Taneja, & Vriend, 2023).

### *Policy*

Policies and regulations at local and global levels influence water transport operations by setting standards for safety, environmental protection, and navigational rules.

Following these policies is essential to ensure smooth and legal operations. Restrictions due to policy will impact transport volumes (Notteboom, Pallis, & Rodrigue, Port Economics, Management and Policy, 2022).

- Policies can directly affect transport efficiency in several ways:
    - **Speed restrictions:** Some areas enforce speed limits to reduce wake impact, which can extend journey times.
    - **Emission and fuel regulations:** Limits on fuel types or emissions may require vessels to operate at reduced power or undergo costly retrofits.
    - **Berthing and cargo handling regulations:** Specific ports may impose regulations working hours, affecting (un)loading times and overall transport schedules.

While policy is an important factor influencing water transport volumes, it will be ignored in this thesis since it falls outside the scope of the research.

# 3. Method and Materials

In the previous chapter, state-of-the-art methods for determining transport capacity were reviewed, and a literature study was conducted to identify key factors influencing water transport systems. This chapter introduces a new method for identifying transport capacity bottlenecks under changing water levels. The method is first explained in detail, after which the Caspian Sea case study is presented and the necessary data are collected.

## 3.1 Methodology

This section outlines the methodology used to identify bottlenecks in water transport systems under changing water levels. A distinction is made between navigational bottlenecks and the system bottleneck.

A navigational bottleneck is a depth-related constraint along a water transport route. Under falling water levels, the shallowest section of the route must be identified to locate this bottleneck. This will be determined qualitatively by dividing the route into distinct sections and determining the most at-risk location.

The system bottleneck will be identified through a sensitivity analysis of the system parameters. This approach will determine which parameters become more important under changing water levels. The analysis will be done quantitatively.

Figure 8 below shows an overview of the two separate bottleneck analyses.

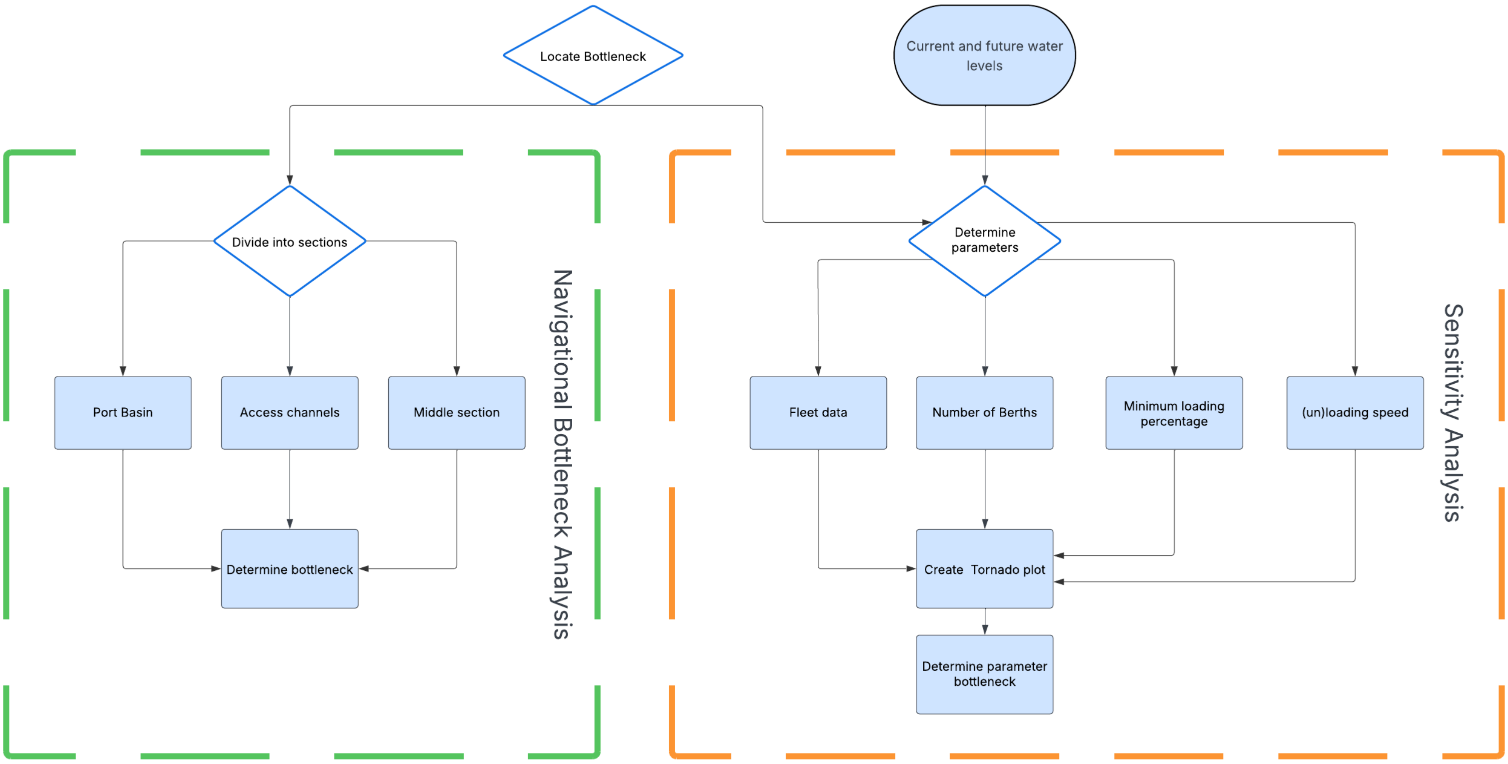


*Figure 8: Schematic overview of methodology.*

### 3.1.1 Navigational bottleneck

A navigational bottleneck is the shallowest part of a water transport route. This depth will determine the amount of draught a vessel is able to sail with, which determines if the vessel can be fully loaded.

The navigational bottleneck will be identified systematically by dividing the transport route in several sections. These sections are:

- Port Basins
- Access channels
- Middle section (Open water stretch between ports)

Figure 9 shows a simple sketch of how this could look like for a transport route.

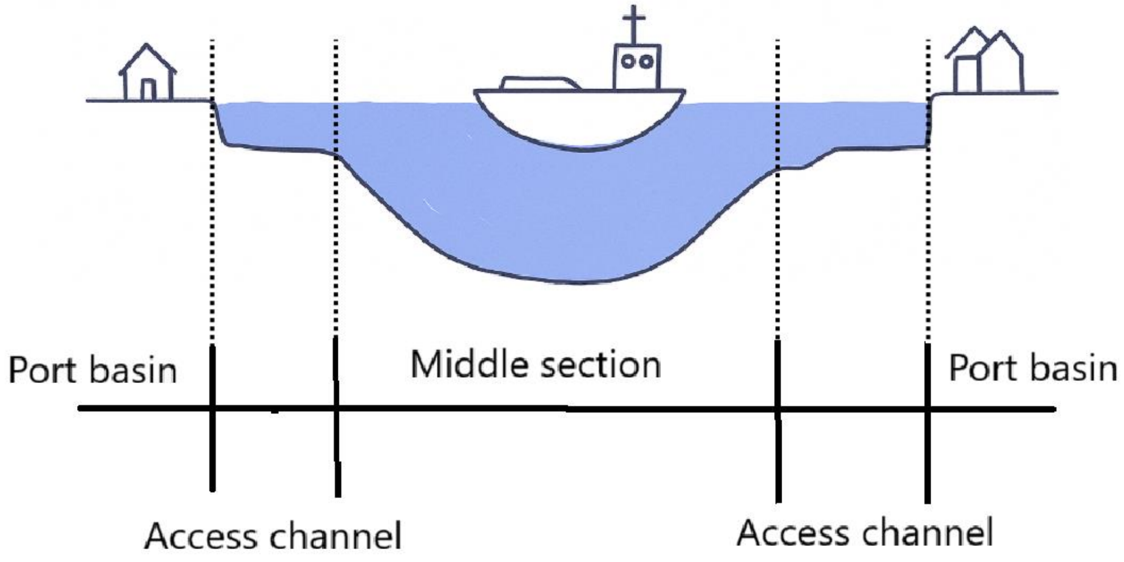


*Figure 9: Schematization of sections of a transport route.*

**Analysis Approach**

Once all relevant bathymetric and port infrastructure data have been compiled, the navigational bottleneck assessment proceeds according to the following steps:

1. Divide the route into the three main sections: port areas, access channels, and the middle section.
2. Gather and interpret available data for each section, including bathymetric depth, infrastructure age, and guaranteed channel depths.

3. Evaluate sensitivity to water level changes by determining which section becomes critical first as water levels fluctuate.

This methodology enables the identification of the weakest link in the transport route from a navigability standpoint, thereby supporting the development of adaptive strategies for infrastructure resilience under changing water levels.

### 3.1.2 OpenCLSim

Before introducing the sensitivity analysis, background information on OpenCLSim is provided to clarify the workings of the simulation used.

OpenCLSim is an open-source python library used for simulating discrete deterministic maritime logistical operations. It is developed by a collaboration of TU Delft, Van Oord, Witteveen+Bos and Deltares. The package allows the user to create their own transport system and choose which features will apply. The user can define site locations for ports or anchorages, and they can create individual vessels with their specific properties, which together will form a fleet. Since sailing routes are usually not straight lines the ‘route’ feature is used to be able to calculate sailing distances. It is especially useful because the user can set up the cycles a vessel goes through.

The package uses a simulation package called Simpy. This is a discrete event simulation package which helps creating logical processes for the vessels and cargo. This package also helps getting timestamps of all steps in the simulation.

OpenCLSim includes example notebooks to guide users in setting up simulations. For this thesis, a custom script was developed to simulate transport operations between two ports, Aktau and Baku. The simulation involves the exchange of a single type of cargo, with vessels returning empty to their origin for simplicity. More complex scenarios, such as including additional ports, multiple cargo types interacting, or two-way transport, fall outside the scope of this research due to their complexity. This limitation does not undermine the study’s objectives, as the focus is on determining relative changes in transport capacity rather than precise absolute values.

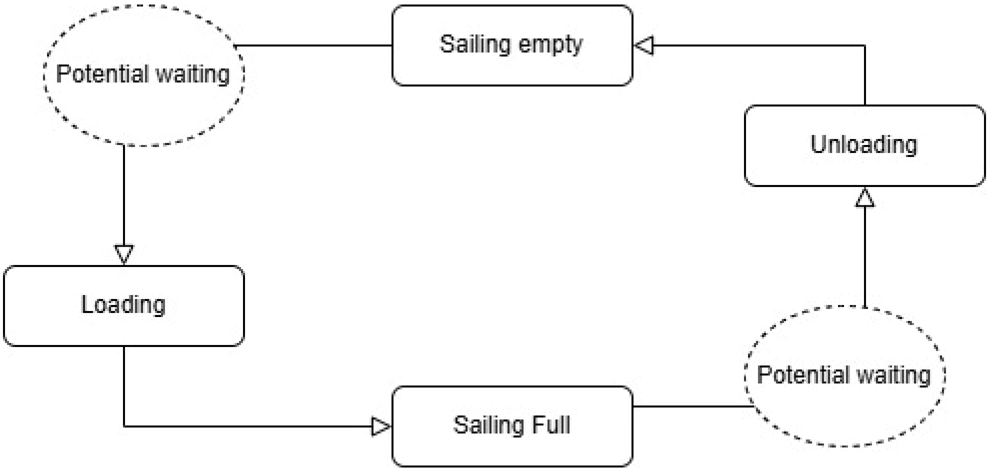


*Figure 10: Flowchart of processes.*

Figure 10 provides a chronological overview of the processes a vessel undergoes during the simulation. As previously explained, vessels are simulated to return empty after completing their deliveries. Potential waiting times occur when all berths are occupied by other vessels. In such cases, the vessel must wait until a berth becomes available before it can moor. Prior to the four main processes, a check is done to see if the vessel can sail based on water levels and how full it can be loaded to still sail safely.

Figure 11 shows a chart if how data is translated into the building blocks of the script, and which outputs are expected. The water level data is always a daily water level of the shallowest part of the route for 365 days in a year. A custom-made script ensures that the simulation checks for each vessel at all times if the water depth is sufficient to sail the whole route, and how full these can be loaded. When water depths are too low, vessels will lay idle until there is enough depth, or the simulation ends.

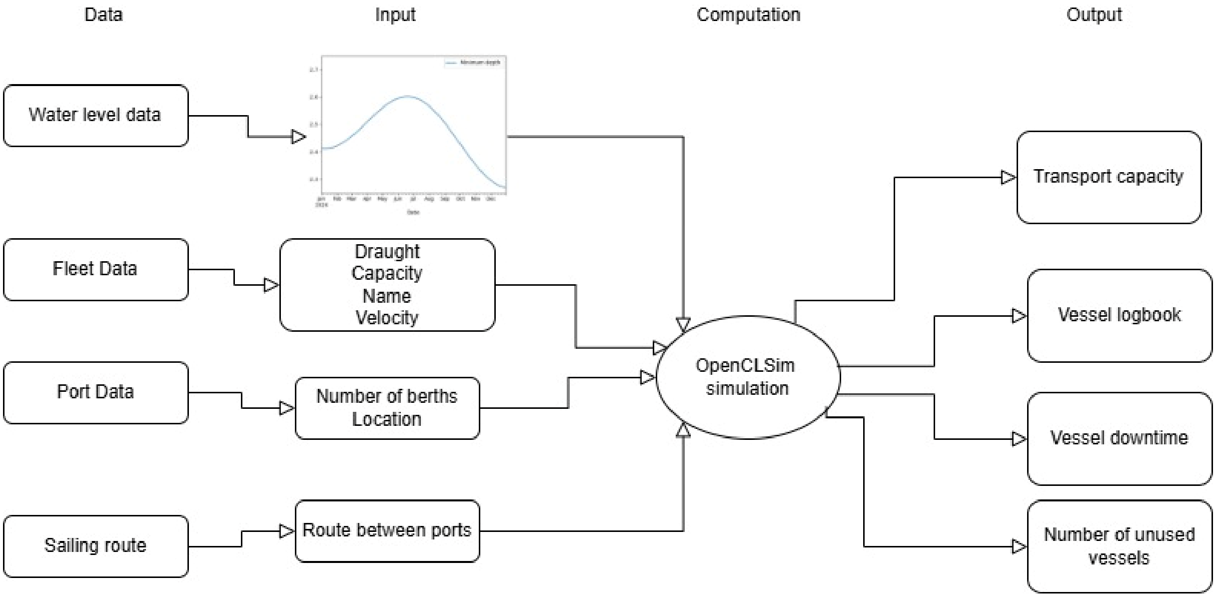


*Figure 11: Flowchart showing input and output of the model.*

### 3.1.3 Sensitivity analysis

The previous section showed the working of the python script to calculate transport capacity, with several parameters as input. The goal of the sensitivity analysis is to view how the transport capacity reacts to changes in parameters, combined with changes in water levels. The sensitivity analysis will vary water depths with continuous intervals until there is no more transport possible. These water depths can then be linked to future scenarios, allowing to determine when the effects of such reductions may occur.

To do this the following steps are required:

1. **Data collection:** Gather relevant data on vessel characteristics, cargo types, port infrastructure, and water levels.

2. **Develop base case scenario:** Construct a representative baseline scenario that differentiates between separate cargo types. This base case attempts to mirror the current situation of the transport network.

3. **Model validation:** Validate the simulation model and its base case parameters by comparing output against real world transport volumes, ensuring realistic behaviour.

4. **Determine capacity loss thresholds:** Determine at which water level the transport capacity falls below 50%.

5. **Parameter variation:** Conduct a one-at-a-time sensitivity analysis, varying each parameter individually while also adjusting water depths.

6. **Sensitivity calculation:** Quantify the sensitivity of transport capacity to each parameter under both current and future water levels.

7. **Visual comparison:** Present and compare the results in a tornado plot to identify the most influential parameters.

These steps will be individually explained.

**Data collection:**

A wide range of input data is required to perform the full sensitivity analysis. This data supports the construction of the simulation model, its validation, and the development of future scenarios. The key data categories are outlined below.

- **Historic water levels**: Time series of observed water levels are needed to understand seasonal and long-term variations. These form the basis for extrapolating depth reduction scenarios.
- **Projected water levels**: If available, water level forecasts or scenario studies are used to estimate when critical depth thresholds may be reached. These can be based on climate models, regional hydrological projections, or expert assessments.
- **Transport volumes**: Recent transport data is required to validate the model. This includes total cargo volumes per year and, if possible, a breakdown by cargo type and direction.
- **Port properties**: Information on port infrastructure includes location, number of berths, average loading and unloading times, and whether berths are dedicated to specific cargo types or vessel classes.
- **Fleet properties**: Data on the operating fleet includes the routes taken by vessels, their draught (both empty and fully loaded), sailing speed, cargo type, and capacity. This also includes the total number of vessels in operation for each cargo flow.

All data should be sourced from reliable institutions, such as port authorities, vessel operators, hydrological agencies, or public databases. In cases where data is not publicly available, reasonable assumptions can be made and documented accordingly.

**Base case scenario:**

The base case scenario provides a foundation for the sensitivity analysis by defining a reference situation against which variations in key parameters can be assessed. While the representation of total transport volumes and fleet composition is not fully accurate, this does not significantly impact the analysis since the focus is on percentual sensitivity rather than absolute transport capacity. The goal is to evaluate how changes in different parameters relate to each other, rather than determining exact transport numbers.

A well-defined base case is essential because:

- It establishes a neutral benchmark to compare changes in transport capacity.
- It helps validate the model in comparison to real-world transport volumes.
- It allows for meaningful relative comparisons between different parameters.
- It helps reviewing which parameters can be varied further on in the analysis.

- It supports scenario evaluation by maintaining a consistent reference point before testing parameter variations.

**Model validation:**

Once the base case has been established, the model must be validated to ensure the accuracy and reliability of the results. This step verifies whether both the simulation logic and the chosen base case parameters reflect real-world conditions.

Validation is performed by comparing the simulated annual transport volumes to observed transport volumes along the same route. The base case scenario is run, and the model output is compared to recent data on actual transported volumes. If the simulated values are of the same order of magnitude as the observed figures, the model can be considered sufficiently accurate for the purposes of sensitivity analysis.

If the simulated values deviate significantly from reality, this may indicate errors in the model setup or unrealistic assumptions in the base case. For example, the simulated fleet size may be too small compared to the number of vessels operating on the route in practice, leading to an underestimation of total transport capacity. In such cases, the assumptions and parameters must be revisited before proceeding.

**Determine capacity loss threshold:**

This intermediate step identifies how the transport capacity is affected by declining water levels. It helps highlight the water depths at which capacity reductions are most significant.

To begin, a step size must be chosen to incrementally reduce the average water level from the base case. This step size should balance detail with computational efficiency. The simulation is then run for each depth level, calculating the resulting transport capacity for each cargo type.

The outcome is a series of curves showing the relationship between water depth and transport capacity. An example of this can be seen in Figure 12.These curves provide a visual overview of how capacity declines for three separate simulations with different cargo types.

From these results, the depth at which transport capacity is reduced to 50% of the base case can be identified for each cargo type. While 50% is used as a reference point in this study, other threshold values can be selected depending on the users criteria.

By overlaying the identified threshold depths with projected future water level scenarios, it becomes possible to estimate when these critical capacity losses may occur.

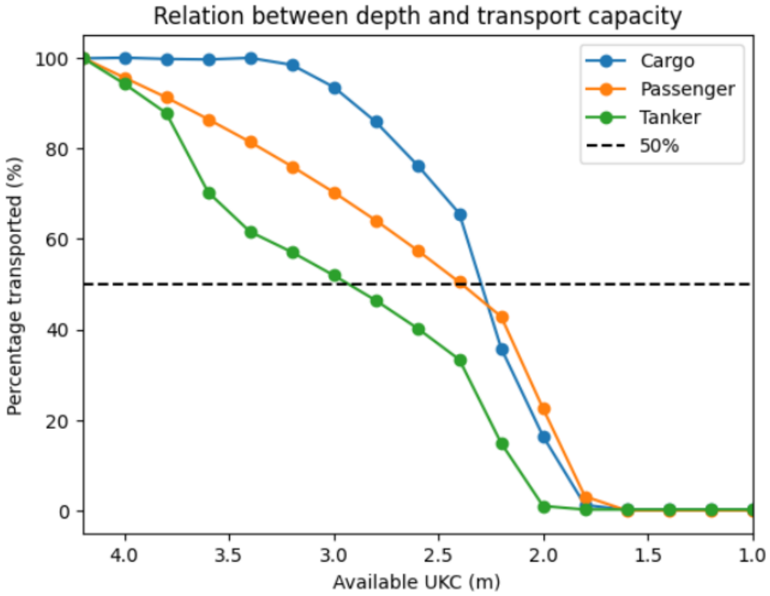


*Figure 12: Example of capacity loss due to depth.*

**Parameter variation:**

To assess the influence of individual parameters on transport capacity under changing water levels, a one-at-a-time sensitivity analysis is performed. This method isolates the effect of each parameter by varying it individually while keeping all other parameters fixed at their base case values.

For each simulation, the following procedure is followed:

1. Select the parameter to be varied and define a realistic range of values.
2. Select a range of water depths. It is recommended to start at the current water depth, down to a water depth where no transport is possible, with a step size that allows for acceptable computing times.
3. Run the simulation for each parameter value and all the water depths.
4. Record the resulting transport capacities and compare them to the base case at each depth level.
5. Repeat the process for all selected parameters.

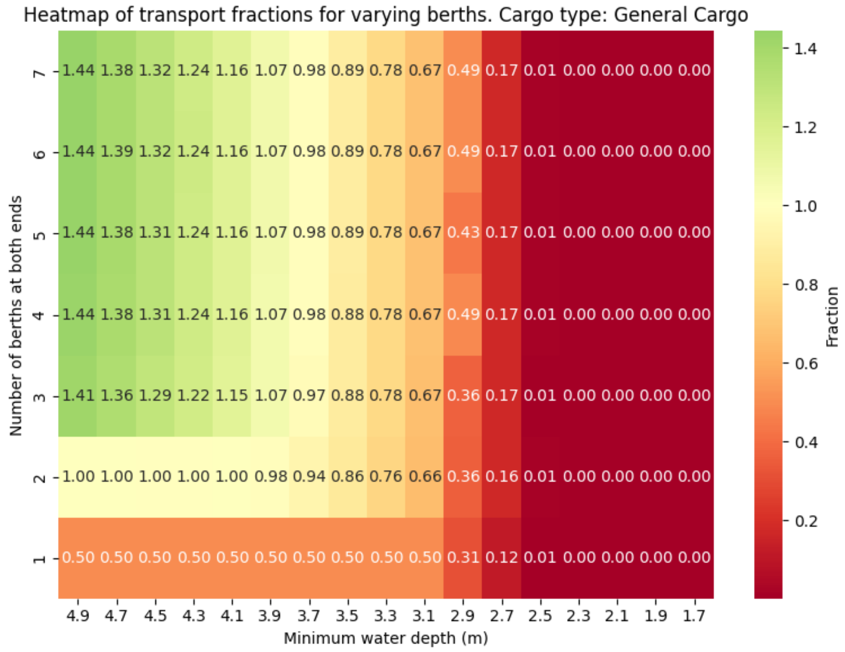
This results in a total number of simulations equal to the product of the number of water depth steps and the number of values in the parameter range:

**Number of simulations = (number of depth steps) × (number of parameter values)**

To manage computational demands, both the step size for water depths and the resolution of parameter ranges should be selected with care.

Next, the transport capacity values from all simulations are normalised by dividing them by the maximum capacity of the base case scenario. This produces a fractionalised capacity scale where anything higher than 1 means transport capacity increases. Values lower than 1 means a decrease in transport capacity.

Using these results, heatmaps can be generated to visualise how transport capacity changes as a function of both water level and parameter value. Figure 13 illustrates an example of such a heatmap.



| Number of berths at both ends | 4.9 | 4.7 | 4.5 | 4.3 | 4.1 | 3.9 | 3.7 | 3.5 | 3.3 | 3.1 | 2.9 | 2.7 | 2.5 | 2.3 | 2.1 | 1.9 | 1.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 1.44 | 1.38 | 1.32 | 1.24 | 1.16 | 1.07 | 0.98 | 0.89 | 0.78 | 0.67 | 0.49 | 0.17 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6 | 1.44 | 1.39 | 1.32 | 1.24 | 1.16 | 1.07 | 0.98 | 0.89 | 0.78 | 0.67 | 0.49 | 0.17 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5 | 1.44 | 1.38 | 1.31 | 1.24 | 1.16 | 1.07 | 0.98 | 0.89 | 0.78 | 0.67 | 0.43 | 0.17 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 | 1.44 | 1.38 | 1.31 | 1.24 | 1.16 | 1.07 | 0.98 | 0.88 | 0.78 | 0.67 | 0.49 | 0.17 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | 1.41 | 1.36 | 1.29 | 1.22 | 1.15 | 1.07 | 0.97 | 0.88 | 0.78 | 0.67 | 0.36 | 0.17 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 0.86 | 0.76 | 0.66 | 0.36 | 0.16 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.31 | 0.12 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |

*Figure 13: Example heatmap, calculated transport capacity for varying berths and water levels.*

To read the heatmap of Figure 13, start at the bottom to see the varying water depth. In this example the number of berths is varied, so this appears on the y-axis. For each combination of these varying parameters, a number is shown in the heatmap. Here 1.00 is the maximum transport at two berths.

So, at a depth of 3.1m and two berths. The transport capacity is 0.66 = 66% of the original transport capacity.

As expected, lower depth results in lower transport capacity and more berths results in more transport capacity. Now it can be seen that transport capacity does not increase above four berths anymore. The heatmap also shows that at one berth, the transport capacity is low, but not affected by changing.

These kinds of observations can be made for all cargo types and all varying parameters.

**Relative sensitivity:**

With the individual influence of each parameter analysed, it is now possible to compare their relative impact on transport capacity under different water level conditions. This comparison is based on evaluating the change in transport performance when each parameter is varied between its worst-case, base case, and best-case values.

For each parameter, the fractional transport capacity from the simulation is recorded at a specific water depth. Consider the example from Figure 13 at an average depth of 2.9m, where the number of berths is varied:

- **Base case:** 2 berths → 0.36
- **Worst case:** 1 berth → 0.31
- **Best case:** 4 berths → 0.49

The percentage change relative to the base case is then calculated using the following formula:

$$\%\ change = \frac{New\ value - Base\ case}{Base\ case} * 100\%$$

Applying this:

- Best case: (0.49−0.36)/0.36×100= +36.1%
- Worst case: (0.31−0.36)/0.36×100= −13.9%

Comparing this to the original water level where:

- **Base case:** 2 berths → 1
- **Worst case:** 1 berth → 0.5
- **Best case:** 4 berths → 1.44

shows that, as water levels fall, the system becomes less sensitive to the number of berths. While the difference between best and worst cases is substantial under current conditions, the effect diminishes at lower depths.

All parameters are evaluated in this way, and the results are visualised in a tornado plot. Each bar in the plot represents the impact of a single parameter, showing its percentage change from the base case for both current and reduced water levels. This is shown in Figure 14, which is an example of how the results may look.

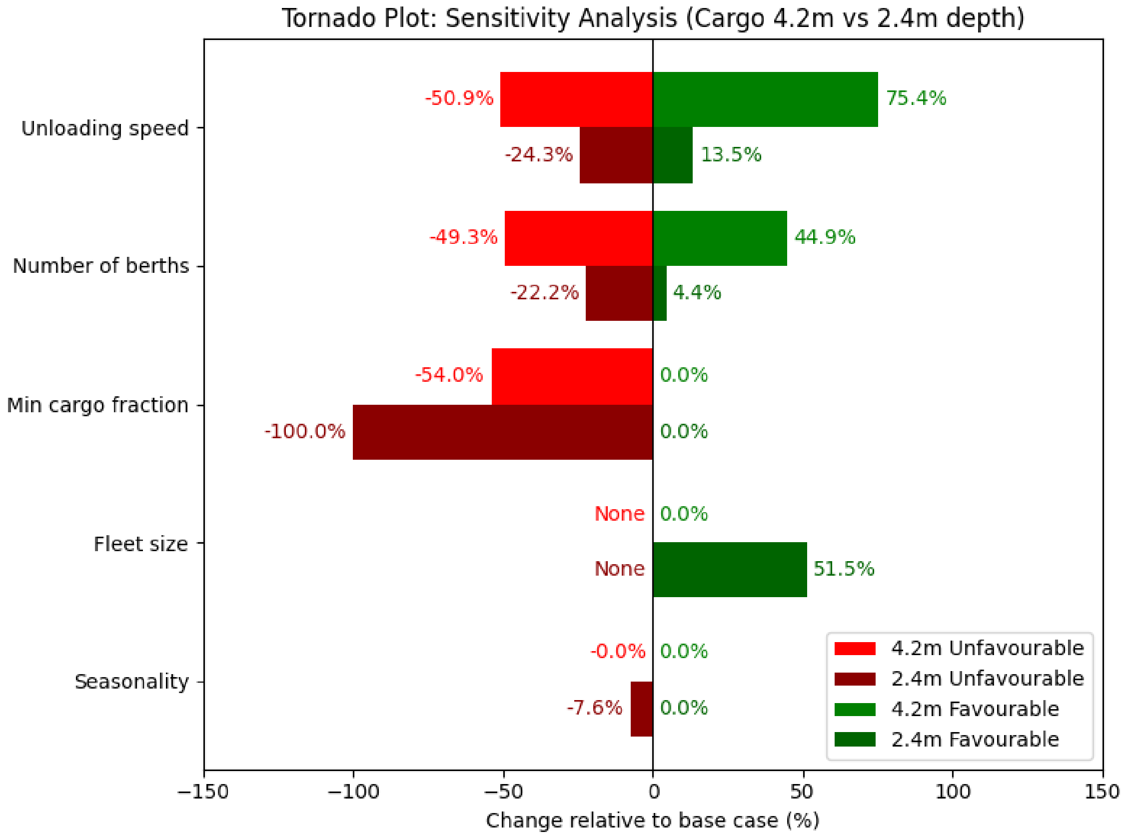


*Figure 14: Example of a tornado plot.*

From this example plot, trends in sensitivity become apparent. The image shows different parameters on the y-axis. Best case scenarios are shown in green and worst-case scenarios in red. There are two bars for each parameter, the upper one is for sensitivity at current water levels. The lower bar is always for sensitivity at lower water levels. This will help identify which parameters become more important as water levels fall.

For example, the loading and unloading rates and the number of berths may be the most influential parameters under current conditions. However, under reduced water levels, these factors may become less critical, while the number of vessels in the fleet becomes increasingly important. This suggests that at current depths, investments in terminal efficiency (e.g., additional cranes) yield the highest returns, whereas in a future scenario with lower water levels, expanding the fleet size may be a more effective adaptation strategy.

Creating such plots will help port authorities and other stakeholder to identify where risks are and where improvements can be made for varying water levels.

## 3.2 Materials

### 3.2.1 Introduction to Caspian Sea case

The previous sections showed a method to identify different bottlenecks in a water transport system. To test this method the case of the Caspian Sea will be researched. Specifically, research will be done on transport between Alat, Azerbaijan and Aktau/Kuryk, Kazakhstan, with one of these routes shown in Figure 15. The following sections will be about gathering data, processing this data, creating future water level scenarios and validating the model. First the relevant ports will be reviewed, then other factors such as fleet composition and route bathymetry will be studied. Then the transport in recent years will be gathered to help validate the base case.

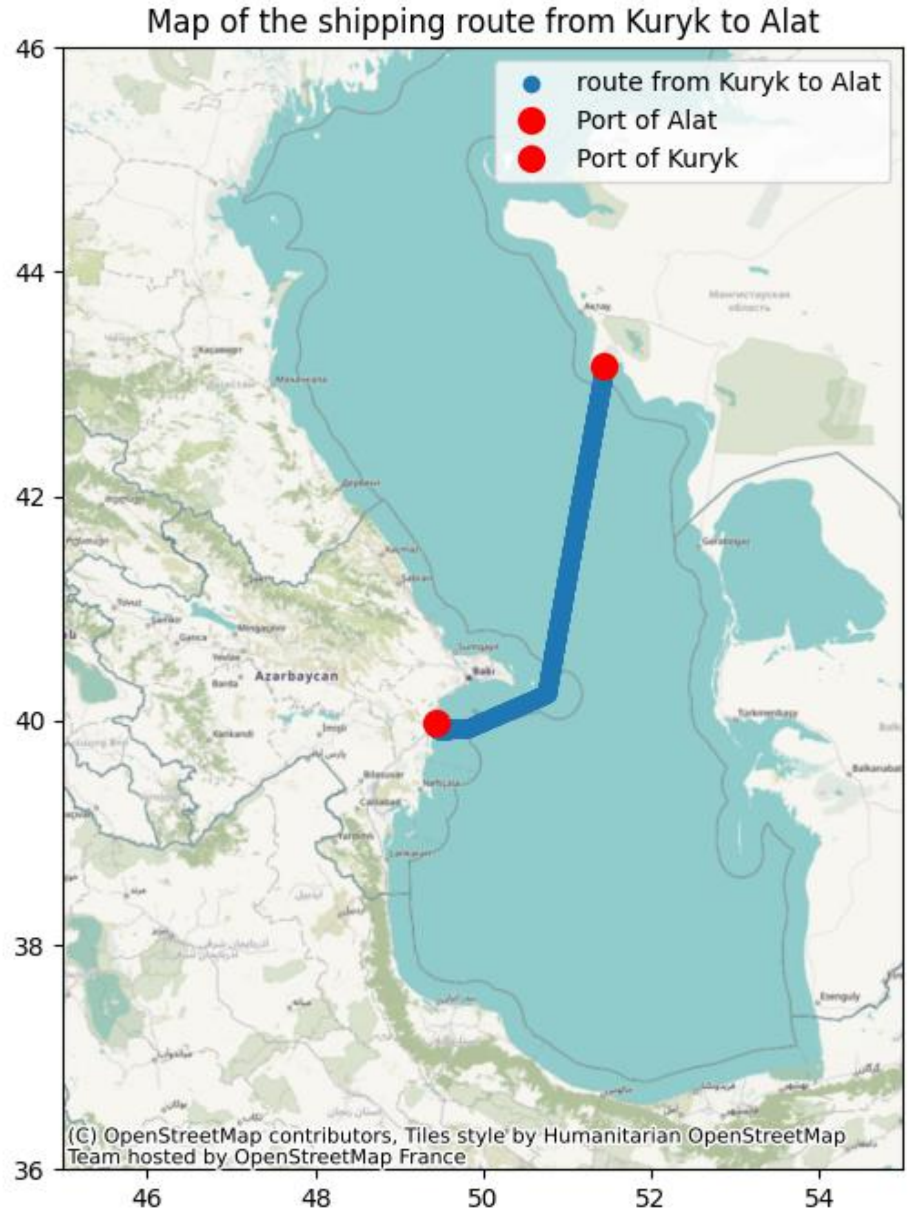


*Figure 15: The Alat-Kuryk route visualized. Based on (OpenStreetmapFoundation, 2025)*

### 3.2.2 Port of Alat

The following sections will examine port age, capacity, number of berths, and other relevant factors. This analysis supports the identification of potential issues in the navigational bottleneck assessment and contributes to defining the base case scenario as well as validating the model.

The Port of Alat, often referred to as the Port of Baku, is in fact a newer facility located just outside the city of Baku. Throughout this thesis, it will be referred to as the Port of Alat. The port became operational in 2018 and can therefore be considered a relatively recent development.

*Figure 16: Aerial view of the Port of Alat (Baku International Sea Trade Port, 2025)*

The capacity of the port has been summarized below (Baku International Sea Trade Port, 2025):

| Cargo type: | No. berths | Total Capacity (million tons) |
|---|---|---|
| Ferry | 2 | 6.2 |
| Container | 2 | 10 |
| Ro-Ro | 2 | 1.8 |
| Total cargo | 7 | 7 |

*Table 2: Port of Alat infrastructure summary. Based on: (Baku International Sea Trade Port, 2025)*

In an interview with Azerbaijani Vision, the spokesperson for 'Baku International Sea Trade Port' has stated that the Alat port is one of the deepest ports in the Caspian Sea. He noted that the bottom will be deepened if water levels decrease in the future. (Azerbaijani Vision, 2022). The depth in the port varies between 7 to 9 meters. (Ports Directory, 2024)

### 3.2.3 Port of Kuryk

The development of the Port of Kuryk in Kazakhstan started in 2011. Strategically connected to its hinterland via a railway station and access to a motorway, the port is a major hub of Kazakhstan's initiative to establish alternative oil routes. Nevertheless, several terminal projects remain at different stages of realisation.

*Figure 17: Schematic planning of the Port of Kuryk (Sarzha Logistics, 2024)*

### Ferry complex

Figure 17 shows a schematic version of the port. The highlighted area shows the ferry complex. The ferry complex has two railway berths and two car berths which can handle 4 million and 2 million tons per year respectively.

Average time of a complete ferry processing cycle:

— single-tier - 6-8 hours.

— two-tier - 10-12 hours, (Port of Kuryk, 2024)

Such operational efficiency enables the port to accommodate up to five ferries daily.

### Liquid Bulk Cargo Terminal

The terminal, covering 26 hectares, is dedicated to the transshipment of oil, oil products, and liquefied petroleum gas (LPG). It is equipped with two berths, each with a depth of 7 meters, allowing for the efficient handling of liquid cargo.

Terminal Capacity:

- Oil and Oil Products: 2,600,000 tons per year
- Liquefied Petroleum Gas (LPG**):** 300,000 tons per year

This setup ensures the terminal can accommodate medium-sized tankers, supporting the region's energy transport needs while operating within the depth constraints of the Caspian Sea. The realization of this terminal has not started and its future is uncertain (bne IntelliNews, 2023).

### Universal Reloading Terminal

This terminal facilitates the transshipment of general, bulk, and container cargo. The terminal is equipped with three berths, each again with a depth of 7 meters, ensuring efficient handling of diverse cargo types.

**Terminal Capacity:**

- **General and Bulk Cargo:** 1,650,000 tons per year
- **Containers:** 150,000 TEU per year

The first phase of this terminal is expected to be completed by 2026, although some aspects of its future implementation remain under review (Thornton, 2025). This facility is critical to supporting the seamless flow of goods across the Caspian region.

**Summary of the future infrastructure:**

| Cargo type: | No. berths | Total Capacity (million tons) |
|---|---|---|
| Ferry(Ro-Ro) | 4 | 6 |
| Liquid | 2 | 2.9 |
| Bulk cargo + container | 3 | 1.8 |

*Table 3: Port of Alat infrastructure summary. Based on: (Port of Kuryk, 2024)*

### 3.2.4 Port of Aktau

The port of Aktau exists in its present form since 1997 (Elkheir). A recent study into the port has concluded: 'The port may have some bottlenecks related to outdated infrastructure and facilities, limiting its capacity to handle larger vessels.' (Beifert, 2024). The study claims that improvements will help the port to become a key transshipment hub in the Caspian Sea.

Recent news shows that the Ministry of Transport of Kazakhstan has initiated dredging works in 2025 (Kwan, 2025). Next to this a container hub will be built with a capacity of 300,000 TEUs. This proves the port will be future proof and no navigational bottleneck.

*Figure 18: Aerial view of the Port of Aktau (Railway Supply, 2024)*

**Summary of the infrastructure:**

The current infrastructure is summarized below (Voetmann, 2017).

| Cargo type: | No. berths | Total Capacity (million tons) |
|---|---|---|
| Ferry(Ro-Ro) | 2 | - |
| Liquid | 3 | 12 |
| General cargo | 3 | 2.5 |
| Grain terminal | 1 | 0.8 |

*Table 4: Port of Aktau infrastructure summary.*

### 3.2.5 Route bathymetry

The analysis begins with the development of a detailed bathymetric profile of the complete route.

Gridded bathymetric data are obtained from the General Bathymetric Chart of the Oceans (Gebco, 2024). This data is imported into QGIS, an open-source Geographic Information System, to extract spatial depth information (QGIS Development Team, 2009). To provide geographical context, a base map is added using the OpenStreetMap plugin (OpenStreetmapFoundation, 2025).

The GEBCO dataset is based on a 15 arc-second grid, equating to approximately 500 × 500 metres per cell (Tozer, et al., 2019). While this resolution is sufficient for identifying general depth trends over extended distances, it does not provide the level of detail required for analysing precise depths within port areas or dredged access channels.

The vessels most common routes are obtained (Marine Traffic, 2025). This will show past tracks of vessels that have sailed the route recently.

Using QGIS's Profile Tool, the route is traced from the origin port to the destination. This tool registers the depth between all points, resulting in a detailed depth profile along the entire route. This geospatial data is particularly valuable for assessing the middle section and identifying depth constraints in access channels.

To evaluate potential bottlenecks within ports, additional data are required. First, the construction or upgrade dates of port terminals are reviewed, under the assumption that more recently developed infrastructure is better adapted to future water level changes.

Water depths in the Caspian Sea vary between 5 and 1025 meters and its basin is divided into three main regions: the shallow northern part, the central region, which is the primary focus of this research, and the deep southern part. Bathymetric data along vessel routes provides crucial insight into potential navigational bottlenecks. For this study, bathymetric profiles will be generated using GEBCO data, which provides global seabed topography at a resolution suitable for large-scale analysis (Gebco, 2024).

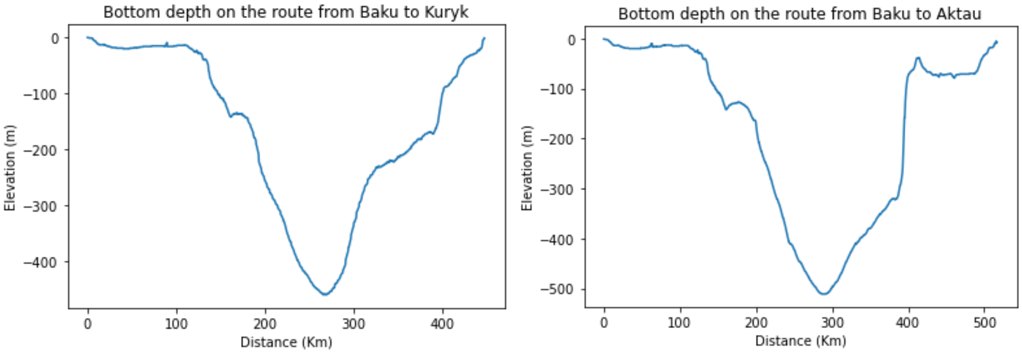


*Figure 19: Routes from Baku to Kazakhstan ports.*

### Depth Profiles Along Key Shipping Routes

Bathymetric profiles along major shipping routes, particularly between Baku (Azerbaijan) and the Kazakh ports of Aktau and Kuryk, reveal significant variations in depth (Figure 19). The first half of the routes to both destinations follow the same path before diverging towards their respective ports.

- **Kazakhstan Side (Aktau & Kuryk)**: Depth increases rapidly offshore from these ports, quickly reaching levels where navigational constraints are negligible.
- **Azerbaijan Side (Baku)**: In contrast, the seabed slope is much more gradual. Over the first 10 kilometres from the port, depths increase only slightly, reaching approximately 10 metres. This limited depth poses a potential navigational bottleneck, particularly in scenarios of falling water levels.

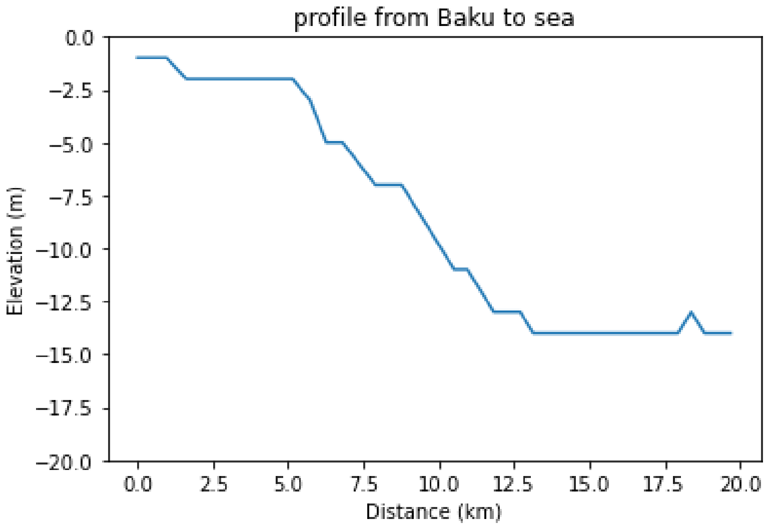


*Figure 20: Profile from Baku to Sea*

### Impact of Falling Water Levels on Navigability

Future declines in Caspian Sea water levels will have varying impacts on different ports, as illustrated in Figure 20.

- **Kazakh Ports (Aktau & Kuryk)**: Since the seabed slopes steeply near these ports, any required dredging is likely to remain close to shore, focusing on increasing depth rather than extending access channels significantly.
- **Azerbaijan Ports (Baku & Others)**: The gradual slope in this area means that dredging efforts must extend several kilometres offshore to maintain accessibility, if water levels fall. This greatly increases operational costs and could introduce logistical challenges for maintaining safe navigation channels.

It is important to note that GEBCO data has a vertical resolution of approximately one metre, which may introduce some discrepancies in depth representation. This explains the large step-like variations in the bathymetric profiles. However, the key takeaway remains the same: the first five kilometres offshore from Baku are particularly shallow, with depths up to five meters making this section the most vulnerable to water level fluctuations.

Figure 21 shows the relation between decline scenarios relative to the -27.5 Baltic Datum, and the change in distance to shore. The graphs of interest are Aktau (1), Baku(2) and Kuryk(8).

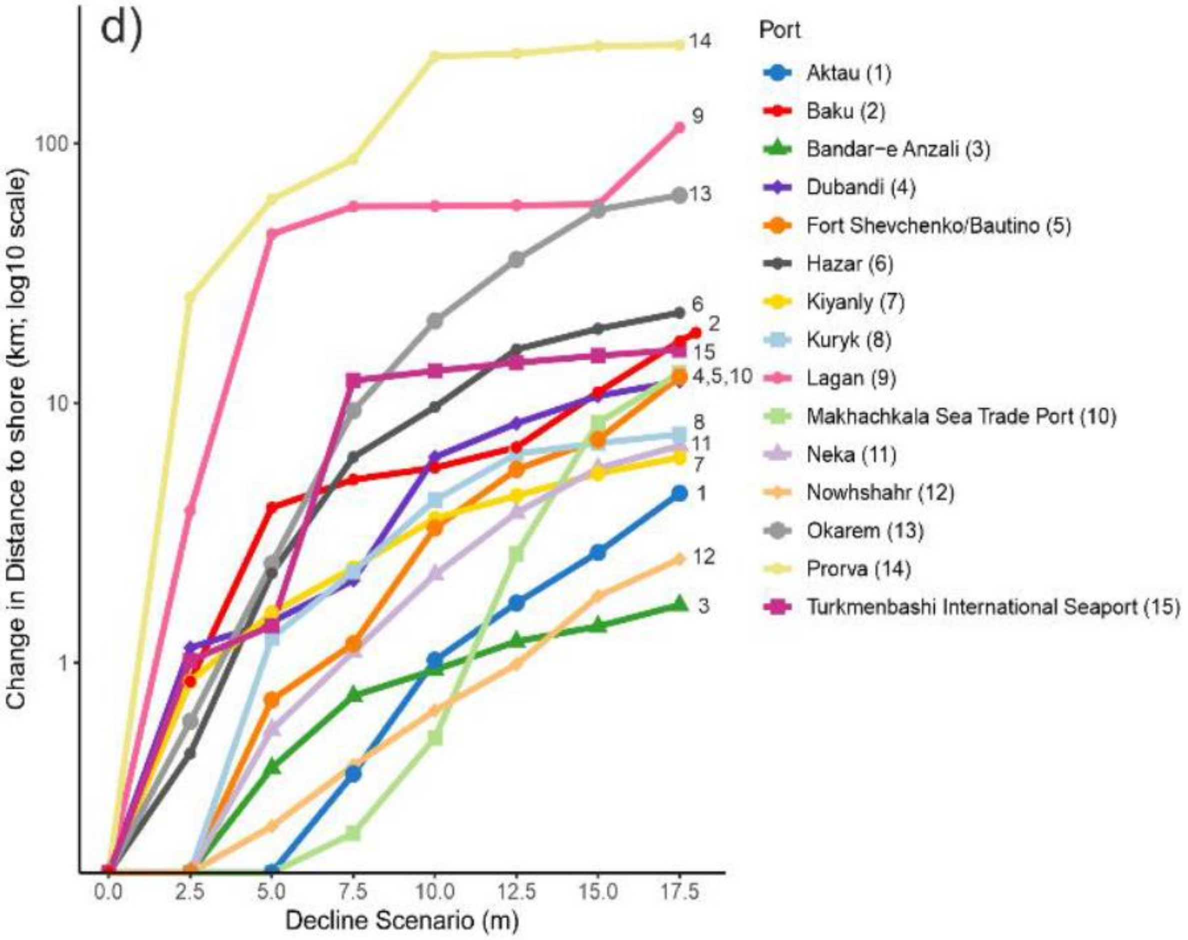


*Figure 21: Increase in distance to coast per decline scenario (Court, et al., 2024).*

The Baku graph indicates that a 2.5m drop in water level leads to a 1km coastline retreat, while a 5m decline results in a retreat of approximately 5km. At this distance, the dredging volume required to maintain an access channel would be impractically high, requiring alternative solutions. Therefore, this thesis will focus on a maximum water level decline scenario of 5 meters.

The change in distance to shore for Aktau only starts at a 5m decline scenario, so is not relevant. For Kuryk this starts at 2.5m and becomes 1km at a 5m decline scenario. This shows that the decline for Baku is worse, but the Kuryk situation cannot be ignored.

### 3.2.6 Fleet data

To accurately assess the fleet operating on the Aktau/Kuryk – Alat route, a detailed and precise dataset is required. The most reliable way to obtain this information is by either inquiring directly at the ports or gathering data from online sources. In this study, MarineTraffic has been identified as the best source. A snapshot of an average afternoon on the Caspian Sea is shown in Figure 22.

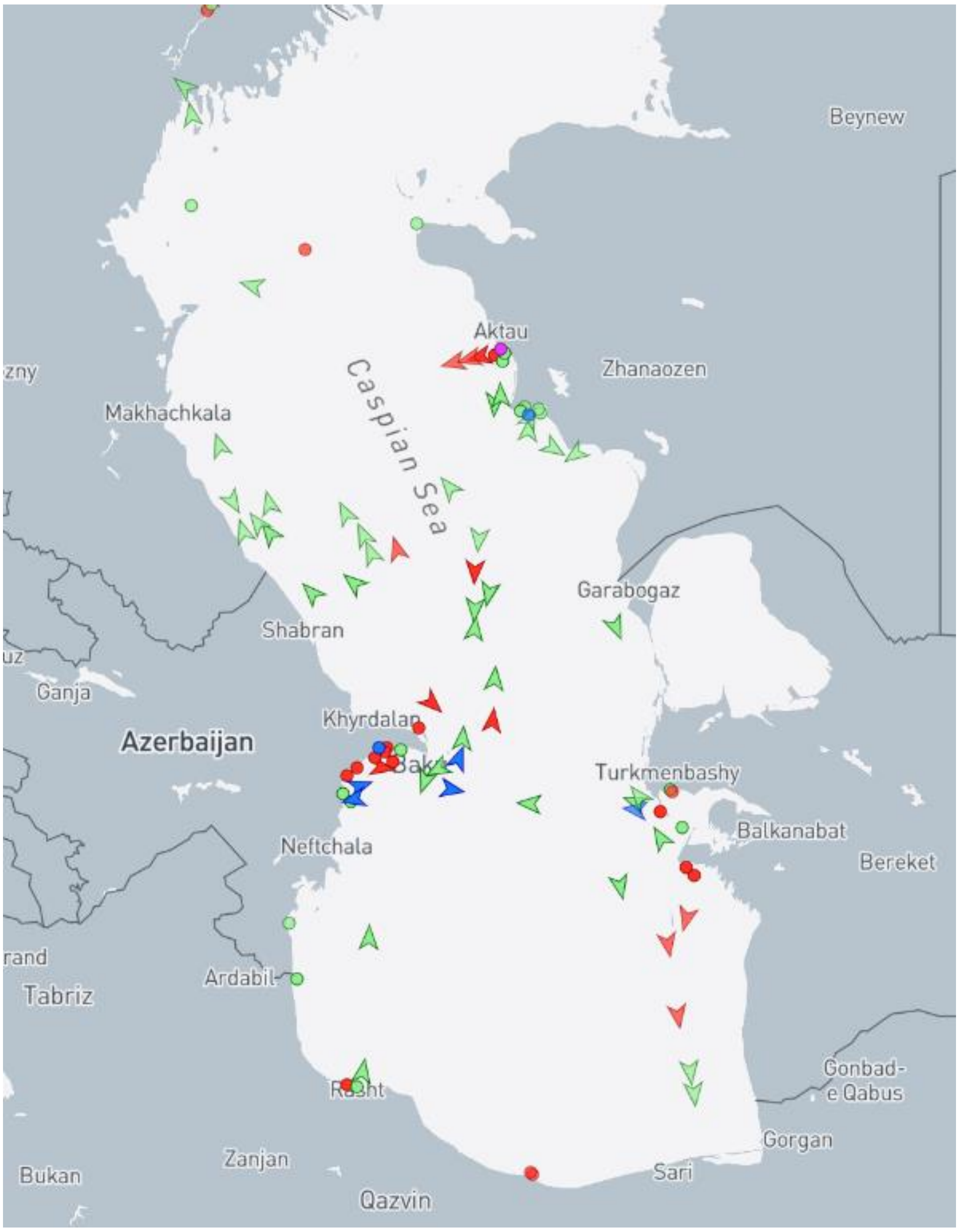


*Figure 22: Schematic overview of traffic on the Caspian Sea (Marine Traffic, 2025).*

MarineTraffic utilises AIS (Automatic Identification System) data to track vessel movements in real time, storing comprehensive information on vessel characteristics. To extract a dataset that best represents the fleet on this route, several filters were applied:

1. **Destination Port:** The vessel's reported destination must be one of the three ports under study (Aktau, Kuryk, or Alat).
2. **Flag State:** Only vessels registered under the Kazakhstan or Azerbaijan flag are included.

3. **Vessel Type:** The dataset is restricted to cargo vessels, passenger vessels, and tankers, ensuring that fishing boats and pleasure craft are excluded.

After applying these filters, the resulting vessel list was exported, including the following key properties:

- Flag
- Vessel Name
- Destination Port
- Reported ETA
- Reported Destination
- Current Port
- IMO Number
- Vessel Type (Generic)
- Time of Latest Position
- Latitude
- Longitude

### Enhancing the Dataset with Additional Vessel Properties

Each vessel has a dedicated information page on MarineTraffic, which provides key details such as:

- Current draught
- Length
- Width

Since these properties were not included in the initial data export, they were manually collected and incorporated into the dataset to create a more comprehensive fleet overview.

It is important to note that the draught value provided by MarineTraffic represents the vessel's current condition rather than its fully loaded or empty draught. As a result, further analysis is required to estimate the full operational draught range under different loading scenarios. Websites of the shipping companies provide the max design draught for all of their vessels. These are obtained from the ASCO and KMTF websites (ASCO,

2025) (KMTF, 2025). The empty vessel draughts are not always provided. So, the choice is made that these are all similar to vessels for which these are known.

Vessel capacity data is not available in the MarineTraffic database. To obtain these values, various sources were consulted, depending on availability for each vessel. The primary source is Vesselfinder which reports vessel-specific properties such as Dead Weight Tonnage and Gross Tonnage (Vesselfinder, 2025).

Individual vessel maximum velocity has to be obtained individually for each vessel.

The fleet consists of 23 vessels, whose properties are summarised in Figure 23. The vessels are separated into three categories:

- Liquid Bulk Tanker
- Passenger (Ro-Ro, Ferry)
- (General) Cargo

Since these cargo types required different vessel types and different berths, they will be simulated independently.

The cargo category will carry general cargo, containers and dry bulk. A full overview of all collected vessel data is available in

Appendix A.

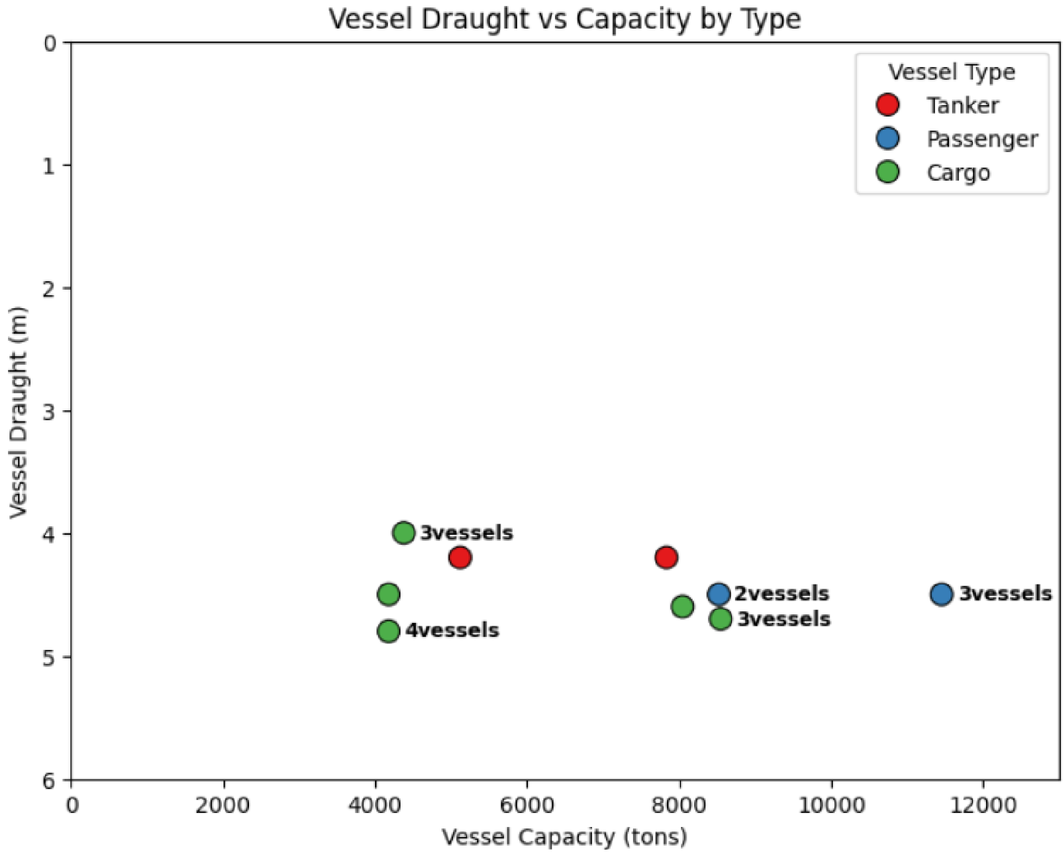


*Figure 23: Visualization of the fleet (Marine Traffic, 2025).*

### 3.2.7 Historical trade volumes

This section will show historical trade volumes on the Caspian Sea route. This will show the importance of the case. It will show the expectations of the future of the route and will help validate the model.

**Transport Volumes**

The Middle Corridor's transport volumes have fluctuated significantly in recent years. Transport had been declining to 586,000 tons in 2021, after which it increased nearly sixfold to 3,332,000 tons in 2024. This is shown in Figure 24. The increase since 2021 is largely because the land route via Russia is less appealing since the conflict in Ukraine (Abbasova & Allison, Can the Middle Corridor be Europe's Middle Ground?, 2025).

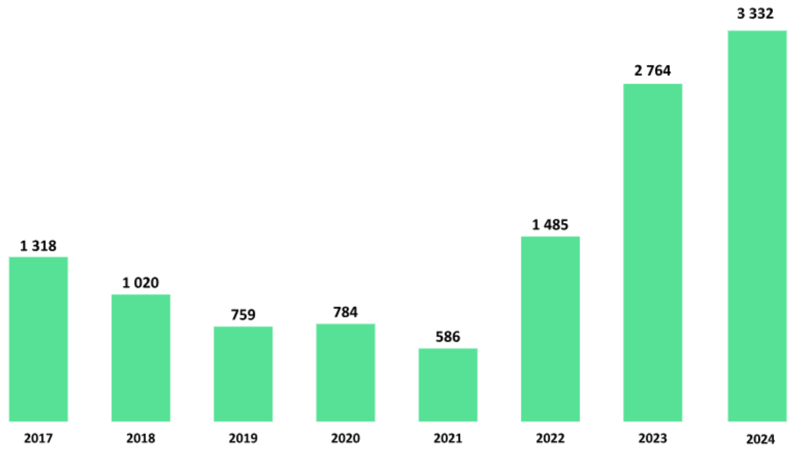


*Figure 24: Transportation volume via Middle Corridor, thousand tons (Middle corridor, sd).*

Container traffic has also been increasing, as seen in Figure 25. In 2024 there were 56,500 TEU containers transported over the middle corridor.

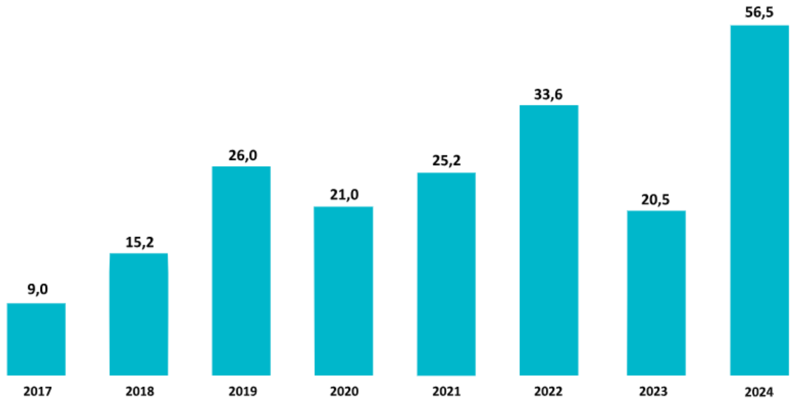


*Figure 25: Container transport volumes via middle corridor, thousand TEU's (Middle corridor, sd)*

Several factors have influenced these variations. For instance, the Russian invasion of Ukraine disrupted the previously dominant Northern Corridor, causing a shift in attention to alternative routes like the Middle Corridor (The German Economic Team, 2022). These geopolitical factors, combined with ongoing infrastructural improvements, have contributed to the increased usage of this route.

### Expectations of Future Transport

The Middle Corridor is destined for substantial growth in throughput (Aguiar, 2025). With improvements in infrastructure and resolution of logistical bottlenecks, it has the potential to become a fast and cost-effective alternative to all-marine routes for transporting goods from China to Europe.

In 2024 transport over the middle corridor rose 70% compared to the year before, reaching 3.4 million tons (Turksoy, 2024). This indicates that countries are becoming aware of the potential, and the transport could increase.

China has signed multiple agreements with Kazakhstan to enhance the middle corridor for transport. Improvements along the whole trade route will be made, including the water transport between Kazakhstan and Azerbaijan (Sharifli, 2024).

## 3.3 Water level data

This section will solely focus on the gathered water level data, and how this is processed to suit the simulation method.

### 3.3.1 Historical water levels

The Caspian Sea has experienced significant fluctuations in water levels throughout history as seen in Figure 26. To ensure consistency in referencing these levels, standardised reference points are used. The most common are the Baltic Datum (BD) and the Caspian Sea Level (CSL), with the CSL defined as 28 metres below the Baltic Datum. As of 2024, the average water level is approximately -29 metres BD, indicating a continued decline. Future projections and expected long-term trends in water levels will be discussed in detail in the following sections.

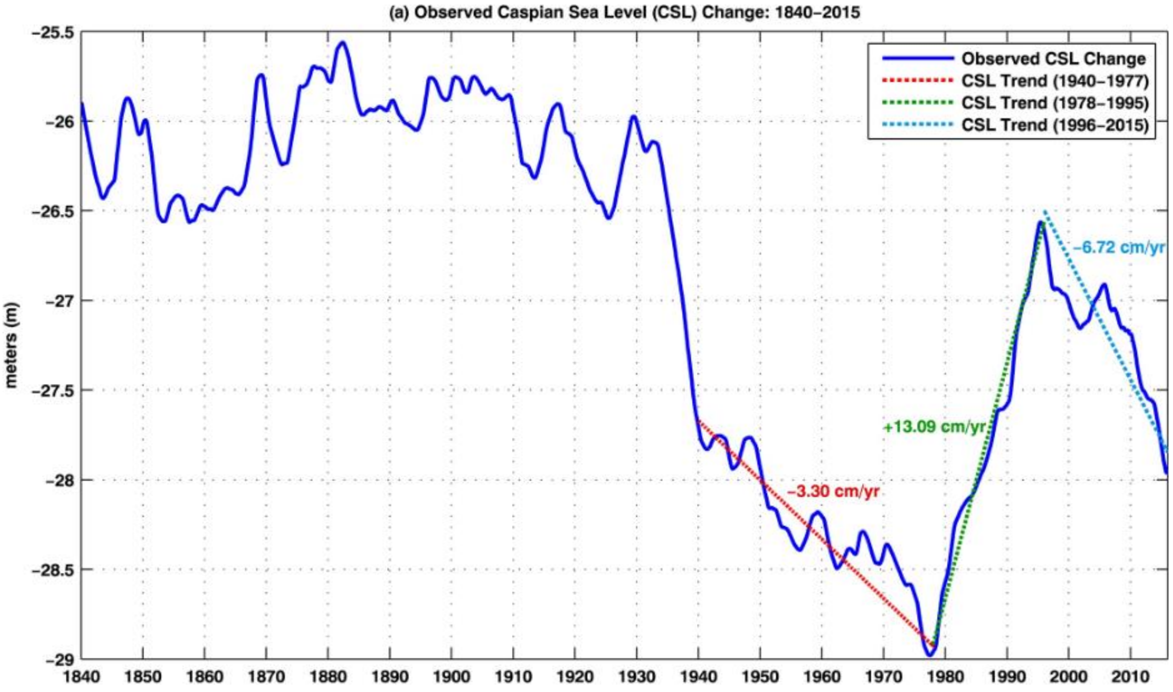


*Figure 26: Graph showing the observed CSL from 1840 to 2015* ***Invalid source specified.***

The average water level in 2024 is around -29m BD. (Forecast* of the Caspian Sea water level for May 9 - 14, 2024, 2024).

**Physical factors influencing water level**

Here the most important historical data of the physical factors within the Caspian Sea will be discussed and their significance will be determined.

*Tide*

There are limited tidal effects in the Caspian Sea. Research has shown that there is a Semidiurnal tide with a height of up to 12 cm. The tidal effects do not exceed 2cm near Baku (Lahijani, Leroy, Arpe, & J.-F. Crétaux, 2023). For the purposes of this thesis, tidal effect will be ignored since they are not significant.

*Wind set-up*

When wind blows in the same direction for a significant amount of time, wind induced water level set-up may occur. The forces of the wind will create pressure on the surface water, causing horizontal flow towards the downwind direction. After a certain amount of time the water levels downwind will increase and decrease upwind.

Wind set-up occurs the most in the northern part of the Caspian Sea. The dominant wind direction is from east to west. An annual set up of 0.5 to 1.5 meters on the western coast is measured there. The middle part of the Caspian sees less set-up due to its different shape and the fact that the water depth is significantly higher than the northern part. This thesis will ignore set-up and set-down. These water level changes only occur when there is a significant of 10m/s wind blowing for a couple of days (Lahijani, Leroy, Arpe, & J.-F. Crétaux, 2023).

*Seasonal changes*

About 80% of the inflow of the Caspian Sea comes from the river Volga (Kalugin & Morozova, 2023). The other 20% is from different rivers and precipitation. Water leaves the sea due to evaporation. The discharge of the Volga varies during the year due to changing temperatures and precipitation. This is shown in the Figure 27.

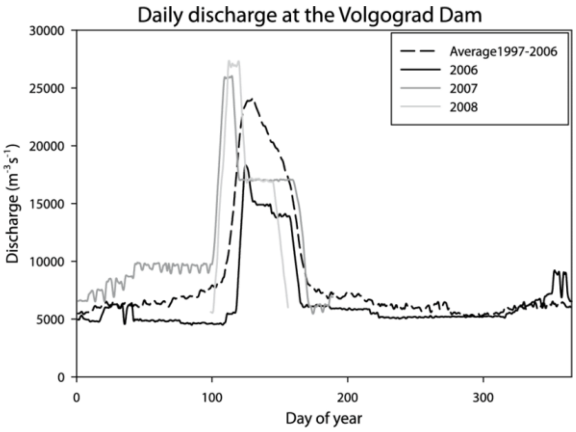


*Figure 27: Volga discharge graph (Kalugin & Morozova, 2023)*

Water levels are higher during the summer and lower in winter. The seasonal variation influences the reachability of the ports. Less transport will be possible in winter. In Chapter 3.3.2 Two data sources are introduced which will help create the future water-level scenarios.

*Water temperature*

The northern part of the Caspian Sea freezes over every year in winter. In the coldest winter this ice sheet can grow all the way down to Bautino, which is located around 130 kilometres north of Aktau (Koenders, 2023).

These parts freeze because the northern region gets colder in winter, and because the water depth is only around five to six metres. Shallow water freezes quicker than deep water, since the total heat stored in the water is lower, so less energy is required to bring the surface to freezing temperature.

If the water level drops, the areas around the port get shallower. Potential freezing is not relevant for port of Baku, since the outside temperature rarely is below the freezing point (Climate and Average Weather Year Round in Baku, sd).

Although there are harsher winters in Aktau and Kuryk, with temperatures lower than -19 degrees Celsius, ice does usually only form for a few days, and only during these severe winters. (Lavrova, Ginzburg, Kostianoy, & Bocharova, 2022). So, a decrease in water depth does not influence the potential freezing.

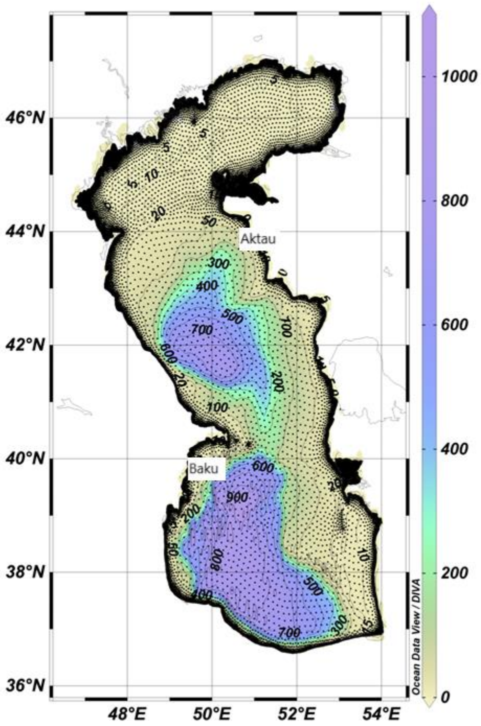


*Figure 28: Bathymetry map of Caspian Sea (Myslenkov, Arkhipkin, & Dobrolyubov, 2018).*

Combining these reasons with the fact that a yearly mean temperature increase is expected due to climate change, the possibility of the routes freezing will be disregarded in this thesis.

### 3.3.2 Historical seasonal variation

**Quantifying seasonality**

Due to changes in inflow and evaporation during the year, seasonal variation occurs in the Caspian Sea. Water levels are higher in summer (June – Augustus) and lower in winter (December – February). This variation will be explored using two different sources and then quantified to create the water level scenarios. The first source is daily local water level data from Aktau for the past five years. The second source is based on satellite data over the Caspian Sea with 10-30 days intervals since 1992. These together will provide a prediction for the amplitude of seasonal variation in future years.

## Aktau data

Figure 29 shows daily water level data measured in Aktau (Annual data on the Caspian Sea regime, 2025). The graph shows a clear downwards trend in average water levels. The seasonality is also visible, since all summers have higher water levels than their preceding winters. The water levels are given in the Caspian Datum.

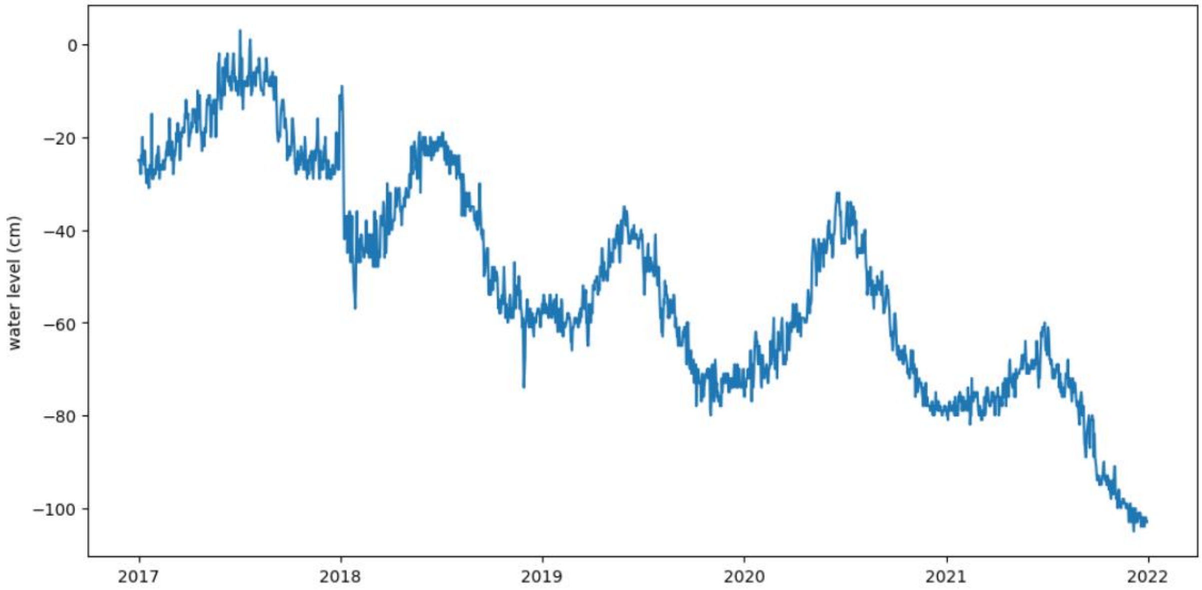


*Figure 29: Water level measurements near Aktau (Annual data on the Caspian Sea regime, 2025).*

## USDA data

The U.S. department of foreign agriculture collects water level data, among other things, from lakes all around the world. Satellites gather data on these lakes every 10-30 days. The collected depth data is shown in the graph below: (USDA Caspian Sea, 2025)

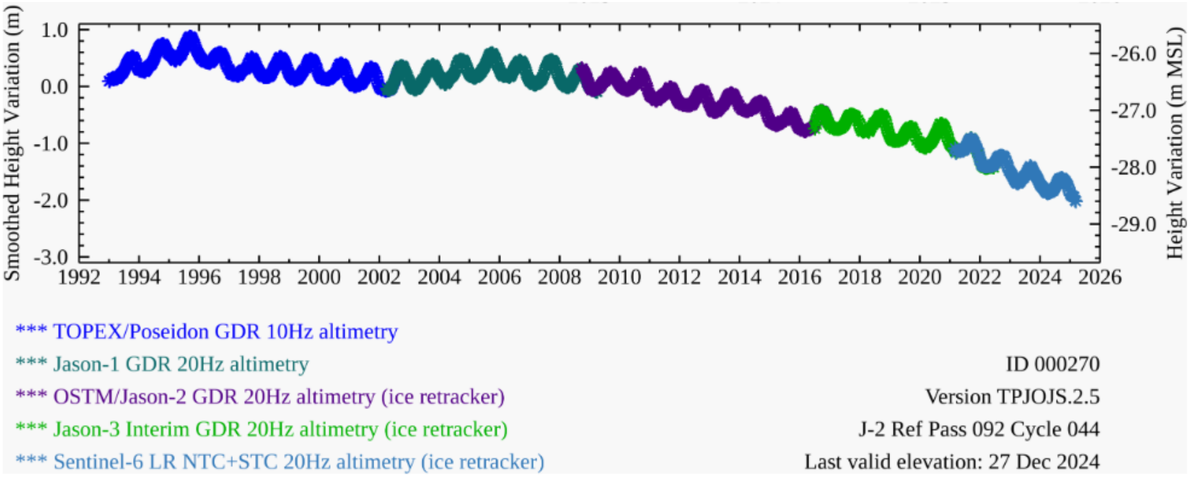


*Figure 30: Satellite water level data (USDA Caspian Sea, 2025).*

The different colors show the changing sattelite missions from which the depth data is collected. There is some overlap between the missions that is not visible in the graph. The graph shows a seasonal water level variation occurring every year. A decline in mean yearly water level can also be seen.

**Preparing data**

By denoising the water level trends and removing the yearly decline, a general variation within each year can be found. This is done by removing the rolling average of the past year. The seasonal variation for the Kazakhstan source is as follows:

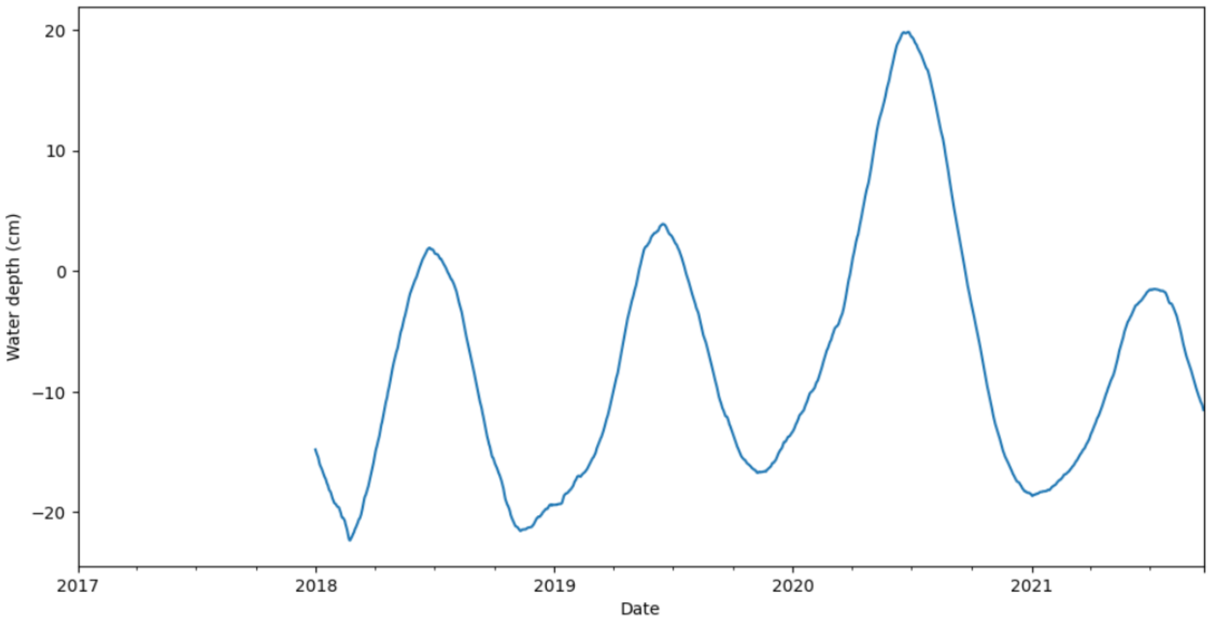


*Figure 31: Seasonal variation in water level where noise is removed.*

The seasonal variation appears to be sinusoidal. Seasonal components can be modelled as a Fourier series for changes in groundwater levels (Jha, 2014). This will be applied to the seasonal variation of the data in this thesis as well.

The formula that is used to fit over the original data is as follows:

$$\bar{T_t} = a + bt + \alpha sin(\omega t + \theta)$$

Here:

'a' = starting point of water level

'b' = linear trend of water level

'alpha' = amplitude of seasonality

'theta' = phase shift of seasonality

The analysis returns the following parameters for the Kazakh example:

```
Parameters:
     a -14.6
     b -0.0399
 alpha 12.9
 theta -1.52
```

The amplitude of the seasonality is seen to be 13 cm. When doing the same analysis for the USDA source the following results are obtained:

```
Parameters:
     a 0.702
     b -0.000173
 alpha 0.175
 theta 0.235
```

Here the alpha is 0.175 m or 18 cm. Both datasets are shown to show a consistency in measurements.

Figure 32 shows both datasets are similar. It is important to note that the starting point are not equal because the USDA data only measures relative depth starting at 0 in 2017, and the Aktau data uses another initial reference number.

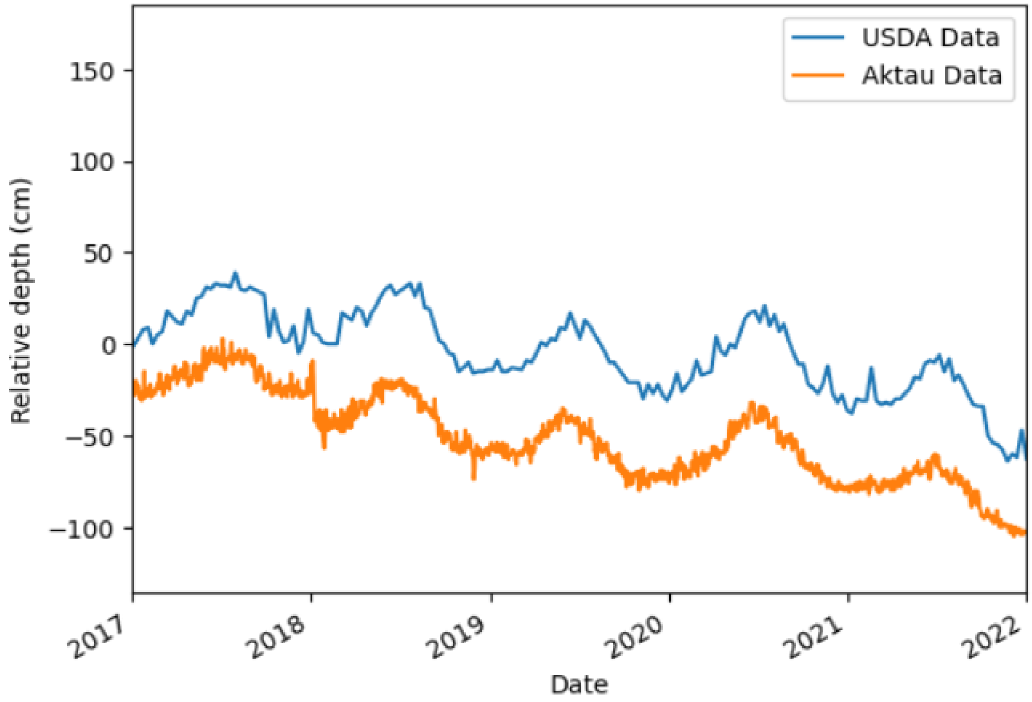


*Figure 32: Comparison of the two water level datasets.*

The amplitude of seasonality varies between 13 cm and 18 cm in both datasets. For the purpose of this analysis, an amplitude of 15 cm has been chosen since this is the average measured seasonal amplitude.

If seasonal amplitude is found to have a more significant effect compared to other inputs, it will be necessary to refine this value to ensure accuracy. However, it is anticipated that seasonality will not play a major role in the context of the Caspian Sea, making the assumption of a 15 cm amplitude likely sufficient for this study.

### 3.3.3 Future average water levels

Future sea level predictions are crucial for predicting future transport capacity. In this section observed long-term trends will be shown for the Caspian Sea case. Next, predictions based on ‘earth modelling systems’ will be explained. These are computational tools to simulate the global behaviour of physical processes. After this, case specific scenarios will be created using long term trends and seasonality.

**Long term trends**

For the last thousands of years, the water level in the Caspian Sea has varied a lot. From -20m BD down to around -32m BD. With these water level fluctuations, the coastline changes as well. A decrease in waterlevel will result in less surface area for the sea.

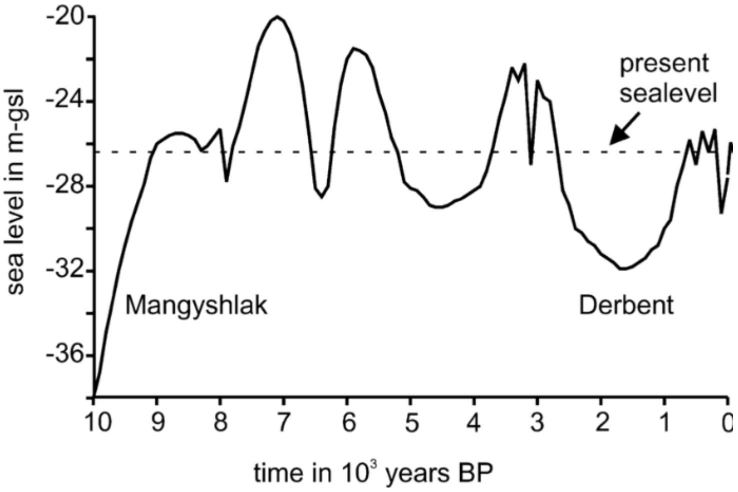


*Figure 33: Historical CSL (Overeem, et al., 2003)*

Since 1840, the waterlevel has fluctuated between -25.5m BD and -29m BD. shows several trends that occurred in the past years.

There have been many attempts to predict future waterlevels. Back in 2012 there were predictions that the CSL would rise between 83 and 163 cm between 2075 and 2100 (Roshan, 2012). Although the report predicted rise in evaporation and a decrease in precipitation in the Caspian Sea, there was a predicted increase in precipitation in the Volga river. It was expected that this would increase the discharge into the Caspian Sea and therefore the water level would increase.

Russian professor Piter Bukharitsin suggests that if there is no human interference, the water level will stabilize around the same depth it stabilized before around 1977 at -29m BD. He predicts that the discharge from the rivers into the sea will increase, and therefore the water level will rise again. He claims that any human interference is bad and that nature will always have natural cycles for the Caspian Sea Level (Bukharitsin, 2023).

The International Journal of Climatology published a paper predicting the CSL by predicting the Volga river runoff for different climate scenarios. The predictions are made with both RCP4.5 and RCP8.5. RCP stands for Representative Concentration Pathway. These are climate scenarios depending on the amount of climate change mitigations. RCP4.5 means medium emissions and RCP8.5 is for buisness as usual, so no mitigation (Pierce, Kalansky, & Cayan, 2018). The report concluded that by the end of the 21st century CSL will drop by 9m for RCP4.5 and by 18m for RCP8.5. (Nandini-Weiss, 2020).

It becomes clear that there are many different water level predictions and that it will be hard to get accurate results.

### Earth system models

Figure 34 shows many different scenarios based on SSP and RCP predictions (Koriche, Singarayer, & Hannah L Cloke, 2021). These are various predictions which take into account the reduction of human emissions and the amount of warming that will occur (Hausfather, 2018). The graph shows that predictions in 2100 vary from -14m BD to -54m BD. These are extreme values and it is expected that the real water level will end up somewhere between the two. It is important to note that the results of these graphs do not yet include water extraction. Because of this, the real expected CSL will end up being lower.

This study will be the only study that is used for water level predictions.

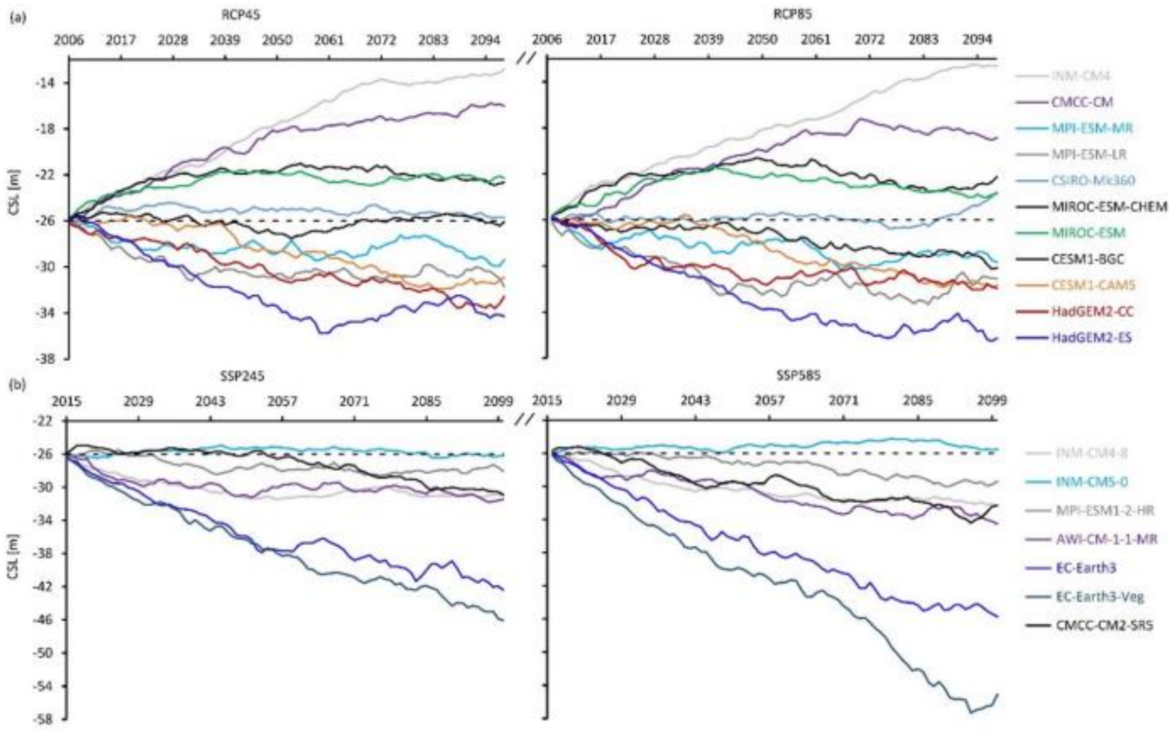


*Figure 34: 4 graphs showing CSL for varying scenarios (Koriche, Singarayer, & Hannah L Cloke, 2021).*

This is a research paper trying to predict water levels in the Caspian Sea, based on multiple earth simulation systems. These models use a so called ‘coupled model intercomparison projects’ (CMIP). The purpose of CMIP is to be standardize climate models and to be able to compare different models to each other (Carlson, Eyring, Wel, & Langendijk, 2022). Eight different models have been used, with varying inputs for each. The used variables are catchment areas and the SSP scenarios. Earth system models divide the planet into a grid of cells, each representing a small portion of the Earth's surface or atmosphere, to perform calculations and simulate interactions across the system. The models have different special geometry and different calculations for climate change impact. Therefore, the results may vary a lot. Figure 35 shows how different models use different areas for the catchment area and the surface area of the Caspian Sea.

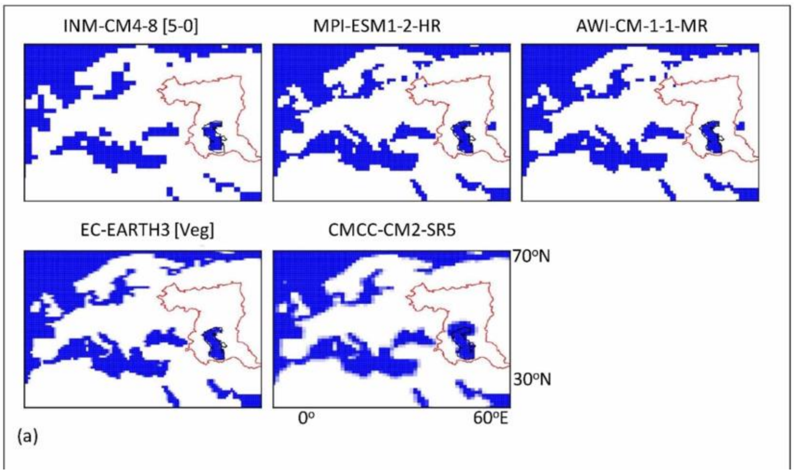


*Figure 35: Caspian Sea catchment areas (outlined in red) for different earth modelling systems (Koriche, Singarayer, & Hannah L Cloke, 2021).*

Koriche continues using the more modern SSP scenarios and plots the Multi Model Mean (MMM). The top two graphs still do not include water extraction. The third graph shows the predicted year that the northern part of the sea is completely dried out, based on the MMM, for both SSP scenarios and for four different water extraction scenarios. This drying coincides with a six-metre water level drop. The bottom yellow bar ends around 2085, so the MMM for no water extraction at all predicts a six-metre water level drop occurring in 2085. This is also the point where the top right graphs MMM line crosses the horizontal line, meaning the same thing.

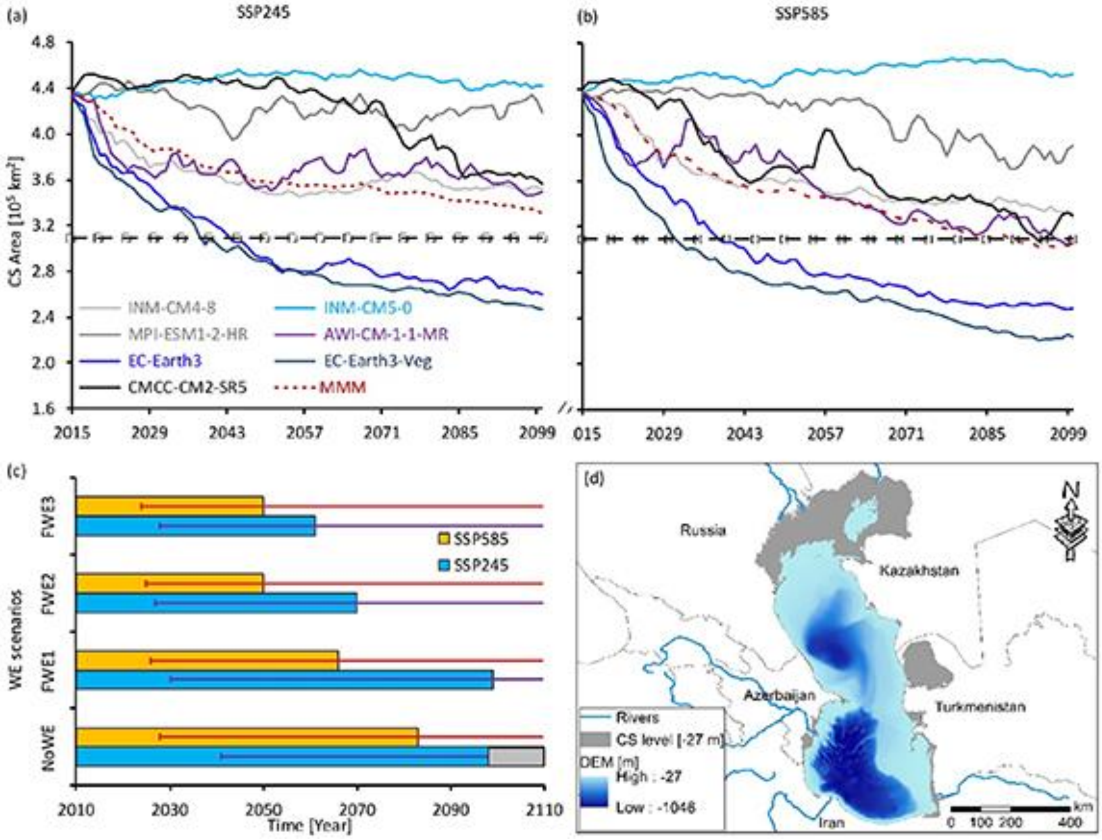


*Figure 36: (a,b) Showing Caspian Sea area for different SSP scenarios and earth modelling systems,. (c) Shows bars of expected 6m water level drop. (d) Shows a map vulnerable to a water level drop of 6m (Koriche, Singarayer, & Hannah L Cloke, 2021).*

Water extraction happens directly from the Caspian Sea, but also from its main water sources, the rivers. The water is used for drinking after filtering, or there is industrial use.

The water extraction scenarios are defined in the paper as follows:

NoWE:

There is no water extraction at all. This is an unrealistic scenario, but the start of the first simulations.

FWE1:

A constant water extraction rate of 20 km$^3$yr$^{-1}$

FWE2:

A constant water extraction rate of 40 km$^3$yr$^{-1}$

FWE3:

A water extraction rate based on expected population change. This varies between 30-50 km$^3$yr$^{-1}$

The scenarios are shown together with previous observations in the figure below:

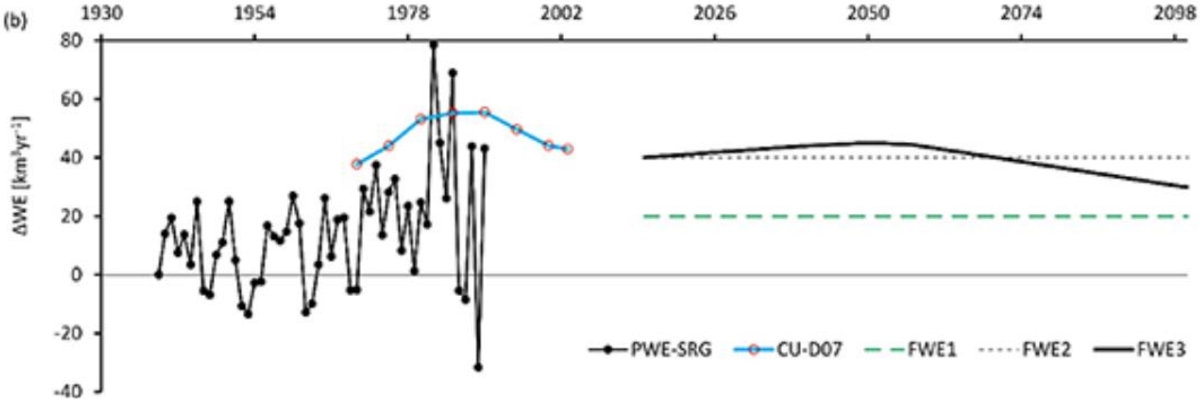


*Figure 37: Graphs showing historical water extraction from the Caspian Sea (Koriche, Singarayer, & Hannah L Cloke, 2021).*

Using the bars from Figure 36. The predictions of a six-meter water level drop are shown below. The values in the cells are the years for which drying up of the northern Caspian Sea is predicted, which is at a six meter water level drop (Koriche, Singarayer, & Hannah L Cloke, 2021).

|  | *Water extraction* |  |  |  |
|---|---|---|---|---|
| *Climate scenario* | NoWE | FWE1 | FWE2 | FWE3 |
| *SSP245* | - | 2100 | 2070 | 2060 |
| *SSP585* | 2085 | 2065 | 2050 | 2050 |

*Table 5: Different scenarios in which year a 6m water level drop is expected.*

The data obtained here will be used in the next section to create scenarios of future water levels.

### 3.3.4 Creating water level scenarios

Previously the average yearly water level change for all scenarios were determined. The assumption is still that the water levels will change linearly in the following years. Using this the average water level change is shown in Figure 38.

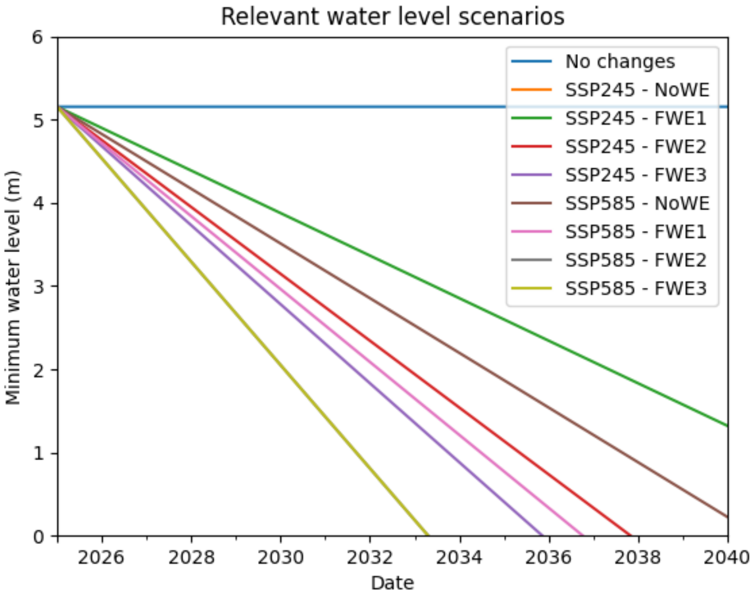


*Figure 38: The minimum water level for 8 different scenarios. Acronyms in the legend indicate the different scenarios, which are explained in Table 5.*

Combining the results for mean water level change of Table 5 and the estimated seasonality (15cm) each year will result in different scenarios for yearly water levels. These are shown in Figure 39.

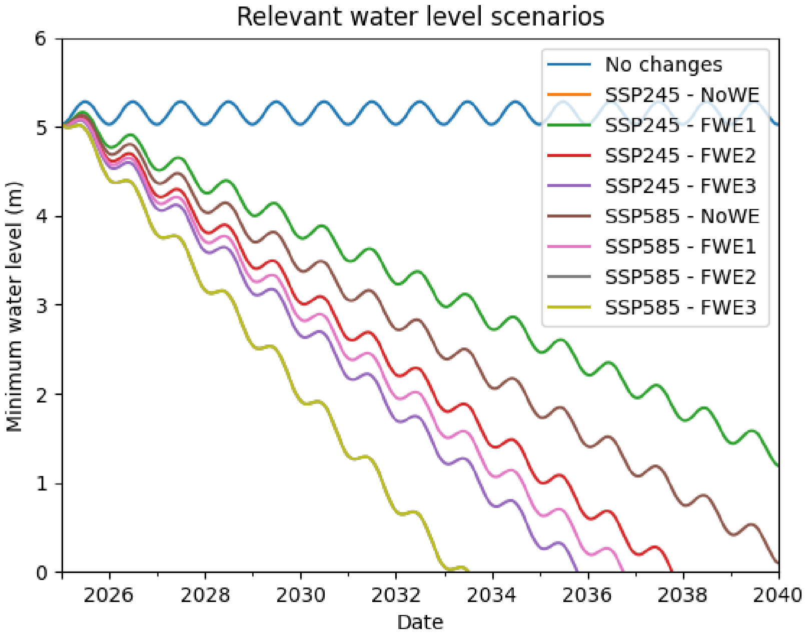


*Figure 39: The minimum water level for 8 different scenarios with seasonal effect added. Acronyms in the legend indicate the different scenarios, which are explained in Table 5.*

Certain scenarios will be excluded from further analysis in this thesis based on their limited practical relevance and overlapping character. The ‘No Water extraction’ scenarios are not considered realistic, as it is highly unlikely that relevant countries will completely cease water withdrawals from contributing rivers or the Caspian Sea. In addition, the FWE2 and FWE3 scenarios show similar trends, as seen in Figure 39. Therefore, these specific scenarios are omitted from the remainder of this study. The remaining scenarios are shown in Figure 40.

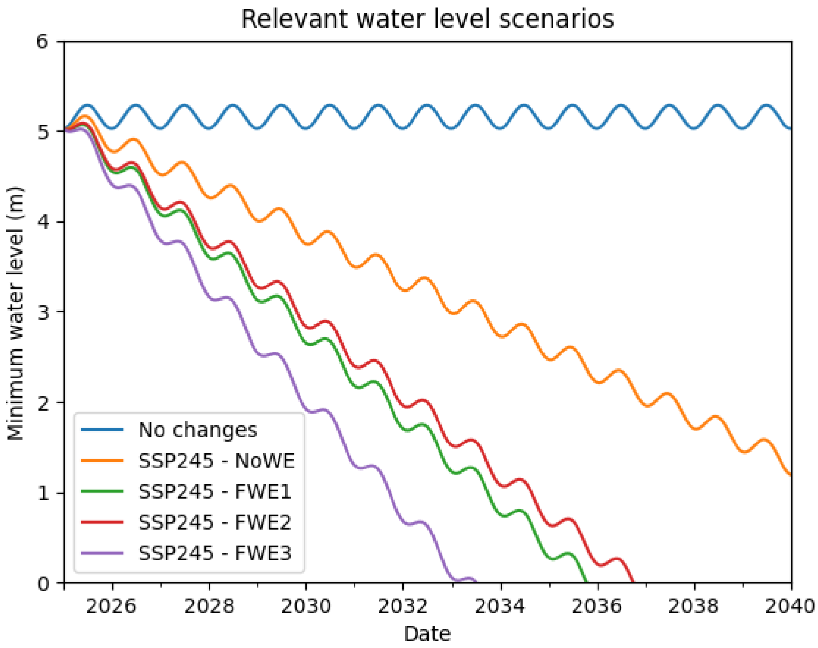


*Figure 40: The minimum water level for 5 different scenarios. Acronyms in the legend indicate the different scenarios, which are explained in Table 5.*

## 3.4 Base case scenario

To maintain consistency, the base case scenario relies on fixed parameter values that approximate the current operational state. These include:

- **Water Level:** The water level in the simulation has been discussed thoroughly in 3.3 The base case water level will be as seen in Figure 41. This is based on the current water level and historical seasonal variability. These water levels have to be converted to UKC to fit the simulation. In shallow waters the minimum UKC can be estimated as 15% of the draught (Marine Public, 2024). The average draught is 4.6m according to the base case.

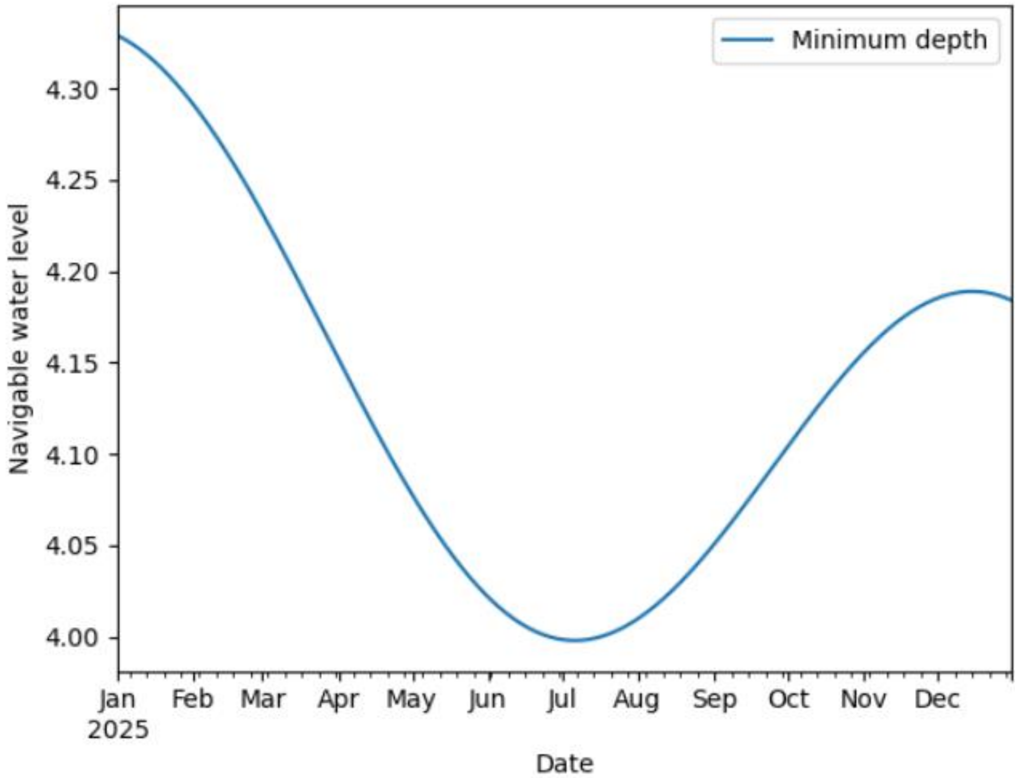


*Figure 41: Base case water depth.*

- **Number of Berths:** The number of berths depend on the cargo type. The berths at the port also service other routes, therefore not all berths in the port are available for the Kazakhstan/Azerbaijan route. So, the following number of berths are allocated:

| | Number of berths: | |
|---|---|---|
| Cargo type: | Alat | Kuryk/Aktau |
| Ferry | 1 | 2 |
| General cargo | 2 | 4 |
| Oil | 1 | 2 |

The simulation will merge the Kuryk and Aktau port together because simulating two routes at the same time using three ports is too complex for the scope of this thesis.

- **Fleet size:** Vessel types with their respective capacities and draughts. These are shown in  3.2.6.

- **Minimum cargo:** A minimum cargo percentage of 20% will be used. This means that vessels will not sail if they cannot be loaded more than 20%. This percentage ensures that vessels will not sail with such low loads that it becomes too expensive to sail.

- **Port Handling Times:** Handling times differ per cargo type. The shown handling times will assume fully loaded vessels. A 50% loaded vessel will take 50% of the handling time. These handling times are determined by reviewing full cycle times at a port (Marine Traffic, 2025).

While these values are not a perfect reflection of real-world transport flows, they provide a sufficient basis for determining the relative importance of different parameters.

## 3.5 Model validity

Section 3.1.3 provided a method to validate the available fleet data. This will prevent an underestimation of the number of vessels in a fleet due to lack of data.

For this thesis three vessel types will be considered:

- Passenger Vessels (Ferries, Roro-vessels, railway ferries)
- Tankers (Oil and other liquid cargo)
- General cargo (Other types of cargo, building materials or containers)

Since the available data does not differentiate between general cargo and container transport, the container transport counts as general cargo.

The calculation is done using the Base Case scenario which will be further defined in 3.4. The results for the yearly transport capacity calculated by the simulation are shown in Figure 42.

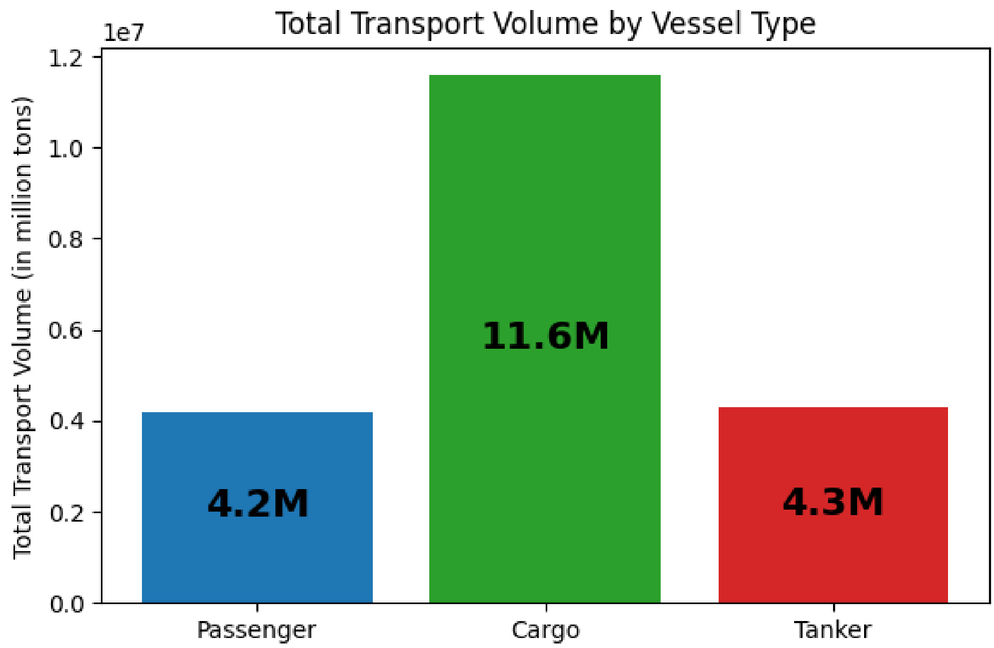


*Figure 42: Bar plot of base case transport volumes.*

Section 3.2.7 showed that the total yearly transport of the middle corridor has varied between one and three million tons total the last few years. Since each individual cargo type has a higher capacity than the total transported in recent years, the conclusion is made that the fleet in the simulation accurately represents the fleet in the real world. The reason that the actual transport is less than the capacity could be that there was not enough demand on the route to sail all the time.

## 3.6 Parameter variability

This section will show all parameters that will be varied and their extreme values. The values are arbitrarily selected. An important notation must be made that the goal is to measure which parameter changes influence the total transport capacity of the system more than others. The resulting tornado plot will show which parameters are more important and require more accurate investigation. The parameters will be varied along with the depth. So, impact of a parameter at each simulation depth can be determined.

Parameters that will be varied for the 'One at a time variation' are listed below:

- Number of berths on either side
- (un)loading rate
- Minimum loading percentage
- Seasonal effects

- Number of vessels in fleet

| Number of berths: | | |
|---|---|---|
| Cargo type: | Alat | Kuryk/Aktau |
| Passenger | 2 | 2 |
| General cargo | 2 | 4 |
| Tanker | 2 | 2 |

The berths of Alat will be 1 for each category in the worst-case scenario. Which is close to the base case scenario. The best-case scenario will be when all berths in the port are available for the chosen route. For Alat this results in the following numbers of berths:

- Ferry: 2 berths
- Tankers: 2 berths
- General Cargo: 5 berths

The ports of Aktau/Kuryk will have the same worst-case scenario of only 1 berth. The best-case scenario is the combined berths of both ports:

- Ferry: 5 berths
- Tankers: 5 berths
- General Cargo: 5 berths

The (un)loading rate is determined from the cycle time in the port. These rates will be varied by doubling and halving these rates.

The Minimum loaded cargo percentage is assumed to be 20% in the base case. A favourable scenario is when vessels sail with any amount of cargo loaded. This means a minimum of 1% loaded. The unfavourable scenario is when vessels only sail when more than 90% loaded.

The Effects of Seasonality are not yet determined. To vary this, the effect of zero seasonality will be tested and the effect of twice as much seasonal changes will be simulated too. The heatmap will help determine if seasonality is an important parameter and maybe should be investigated.

# 4. Results

## 4.1 Bottleneck analysis

To find the navigational bottleneck, the transport route was divided into several sections. Data was gathered for each of the specific sections. Using this, there will be an analysis for the risks of changing water levels associated for each of the sections. The section with the most risk associated with falling water levels will be the navigational bottleneck in the system.

The potential depth related bottlenecks are as follows:

- Port of Alat
- Access channel of Alat
- Middle route across the Caspian Sea
- Port of Kuryk
- Access channel of Kuryk
- Port of Aktau
- Access channel of Aktau

Each sections risks will be assessed and there will be a comment on the likelihood of that section being a navigational bottleneck.

**Port of Alat**

Section 3.2.2 describes the port of Alat in detail. The port is relatively new and statements have been made that the port will be deepened if required, so depths of at least 7 meters will be there at all times. For these reasons it is safe to assume that the port of Alat will **not be a bottleneck.**

**Access channel of Alat**

Section 3.2.5 showed the bathymetry in the access channels for the ports. Figure 20 showed the bottom depth from Baku to sea. The depth did not exceed 3 meters for the first 5 kilometres. After this the water becomes deeper until it hits 13 meters. The 13-meter water level depth continues to 20 km out of port.

Since water levels are expected to fall in the coming years, the bathymetry in the access channel can pose significant challenges. Areas surrounding the access channel will become dry as the water level falls. So, the access channel will have to be fully dredged with no surrounding water. This access channel poses a **significant threat to be a navigational bottleneck.**

**Middle route across the Caspian Sea**

In section 3.2.5 the bathymetry along the whole route is shown. Depth issues clearly only occur in the first kilometres of the route and are no issue in the middle of the Caspian Sea. Here is determined that waves are insignificant based on historical wave heights. For these reasons it is determined that the middle part of the route will **not be a bottleneck for** water transport influenced by changing water levels.

**Port of Kuryk**

Section 3.2.3 describes the Port of Kuryk in detail. The findings are that the port is relatively new and still under development. A fair assumption can be made that the port will be built with future water levels in mind. Since the current expectations are falling water levels, the port will be prepared for it. Therefore, the port of Kuryk will **not be a bottleneck in this system.**

**Port of Aktau**

Section 3.2.4 describes the port of Aktau as an important factor for Kazakhstan water transport. Although the port is relatively old, commitments are announced for new terminals and dredging activities. These changes may take some time to be implemented, which is why **the port of Aktau is seen as the biggest threat of a bottleneck of the three ports.**

**Access channel of Kuryk and Aktau**

Section 3.2.5 has shown that the access channel of Kuryk and Aktau are similar. They both become deep quickly and are nowhere near the low water levels of the Alat access channel. Therefore, these access channels will **not be a bottleneck in this system.**

## 4.2 Base case results

The base case has been simulated across a range of water levels to assess how transport capacity responds to changes in available depth. This analysis allows for a direct relationship to be established between water level and system transport capacity. These results can then be applied to long-term water level scenarios, enabling the prediction of future transport capacity for a given year under an assumed scenario.

Since the transport system handles three distinct cargo types, each associated with its own vessels and dedicated berths, separate simulations have been conducted for each cargo stream. Water depth is represented in the model as the minimum available UKC along the entire route. This value defines the shallowest point at which the vessel must maintain sufficient clearance to operate safely, and thus determines whether a vessel can complete a journey.

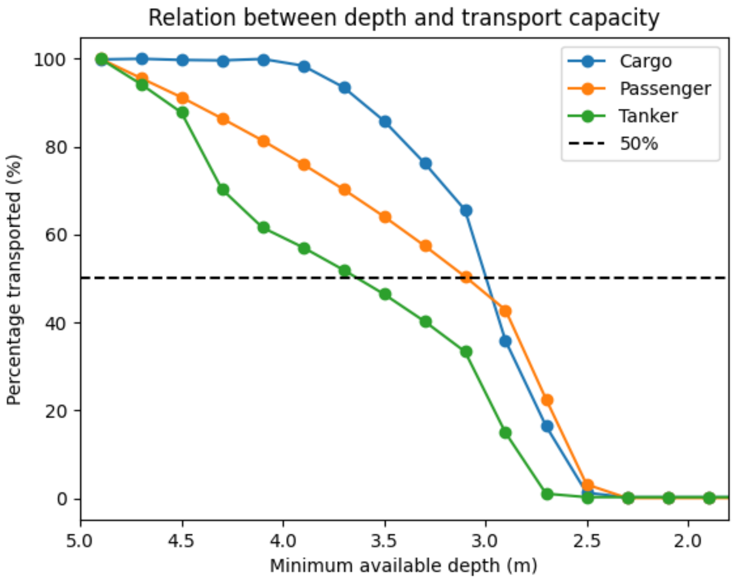


*Figure 43: Results of simulating the base case for various water levels.*

Figure 43 presents the results of simulating the base case scenario for the various water levels, for the three cargo types. Each cargo type begins at 100% transport capacity occurring for the current minimum depth of 5 meters. The results show that cargo vessels maintain near-full capacity between depth values of 5 m and 4 m, after which their performance declines sharply. This indicates that, within this range, water depth is not yet a limiting factor for cargo vessels.

In contrast, the transport capacities of passenger and tanker vessels begin to decline immediately as depth decreases, suggesting that these vessel types are more sensitive to reductions in water depth. The UKC values at which each cargo type reaches 50% of its original capacity are as follows:

- Cargo: 3.0 m
- Passenger: 3.1 m
- Tanker: 3.6 m

These values are plotted in Figure 44. Here the relevant water level scenarios from 3.3.3 are also plotted. The seasonality is not displayed to obtain a clearer image.

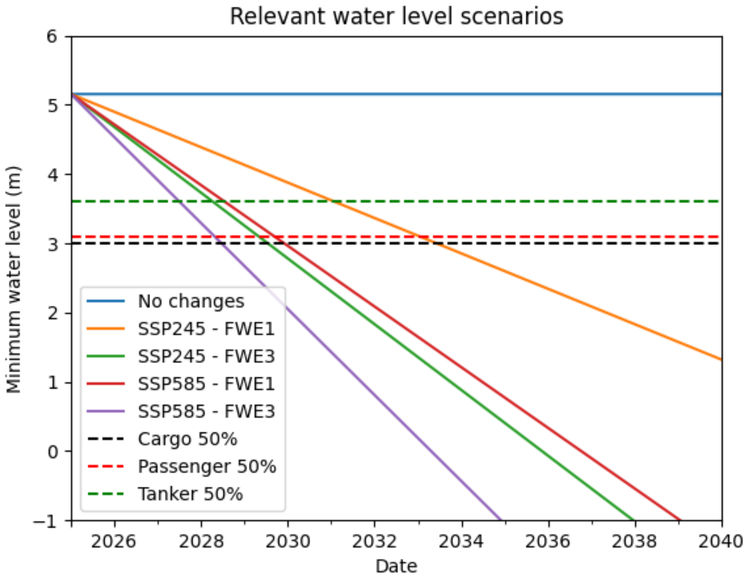


*Figure 44: Figure showing when 50% transport capacity will be reached.*

Based on this figure, the 50% capacity threshold is expected to be reached in the following time frames:

- Cargo: between 2028 and 2033
- Passenger: between 2028 and 2033
- Tanker: between 2027 and 2031

## 4.3 Sensitivity analysis

A sensitivity analysis was conducted to assess how changes in key parameters affect the system. Since the cargo types use different vessels and berths, all three cargo types are analysed separately. First, the individual results are presented. Next, the results are compared to examine how the parameters relate to each other.

### 4.3.1 Parameter variation

**Varying berths:**

This page shows how the transport capacity is affected by varying the number of berths and depth. The number in each cell of the figures is a fraction of the maximum base case value. When a cell is yellow and graded with 1.0, the transport capacity is at the maximum of the base case scenario. When a cell is greenish and graded more than one, the transport capacity has increased with respect to the base case. Red cells indicate a decrease in transport capacity.

Figure 45 shows the simulation results for a varying amount of berths for the general cargo type. It shows that increasing from 2 to 3 berths increase the transport capacity from 1.0 to 1.41 at the current depth. More than this does not seem to have an impact. The difference between 2 and 3 berths decrease as water levels drop. At a water level of 3.5 m the difference is only 0.03 which is 3%.

Figure 46 shows the results for the tanker category. At berths the tanker category is at 1.01 which is a 1% increase. A reduction to only one available berth results in a decrease to 0.86. Again the impact of a different number of berths does reduce as water levels drop.

Figure 47 shows the results for the passenger category. Again, increasing the number of berths to higher than 2 has no impact. If only one berth is operating the terminal would operate at 70% capacity. As water level fall, this difference decreases.

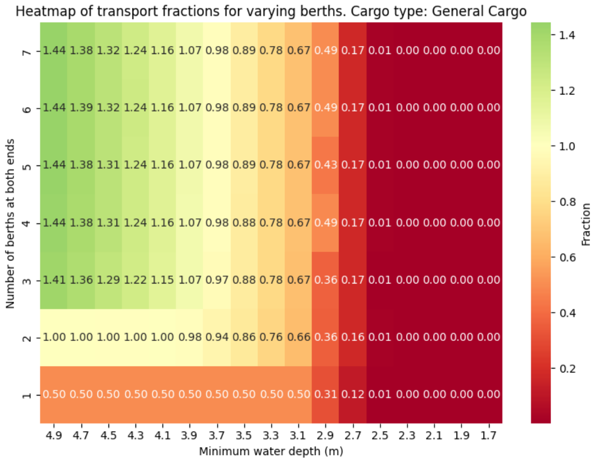


*Figure 45: Heatmap of simulation results, for varying the number of berths for general cargo.*

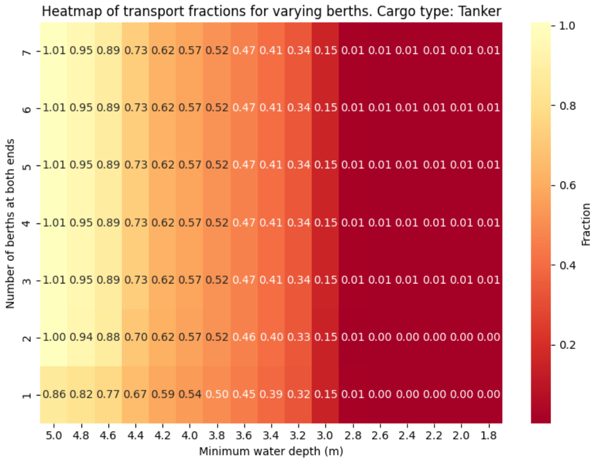


*Figure 46: Heatmap of simulation results, for varying the number of berths for Tankers.*

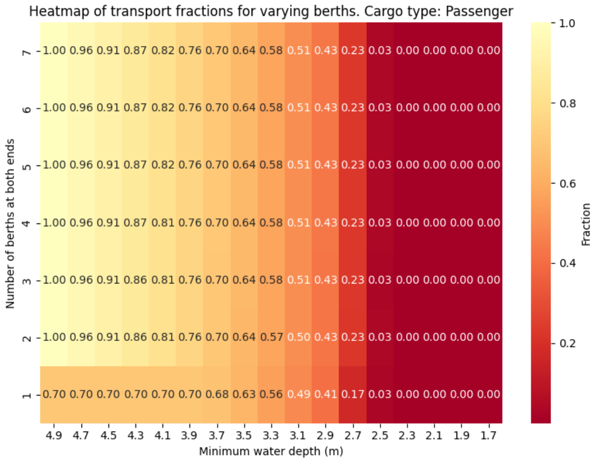


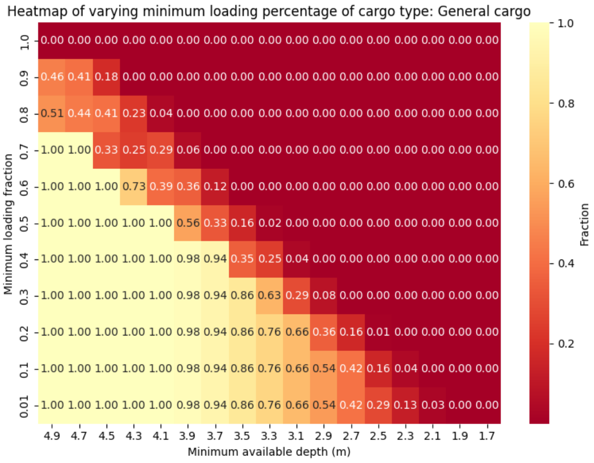
*Figure 47: Heatmap of simulation results, for varying the number of berths for the passenger category.*

## Minimum loading percentage:

Figure 48 shows how the transport capacity changes for a varying minimum loading fraction. It shows that if vessels are only sailing when they can be fully loaded (fraction = 1), even at the current water depth there will be no transport. The figure shows a diagonal line where transport capacity declines drastically if the minimum loading percentage is not reduced. If a choice is made that vessels should sail at at least 50% capacity, transport volumes will decline to 33% when the available depth becomes 3.9m.

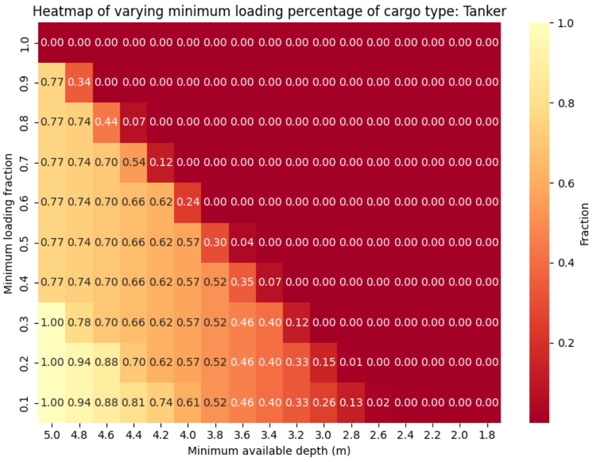
Figure 49 shows the same for the tanker category. Even compared to cargo, tankers are more sensitive to declining water levels. A minimum loading fraction as moderate as 0.4 already leads to noticeable reductions in capacity. Once depths fall below 3.6-3.4 metres, the tanker transport system collapses rapidly unless this restriction is relaxed. The steep diagonal slope in the results indicates that tankers require early and substantial flexibility in loading rules to remain operational.

Figure 50 shows the results for the passenger category. Passenger transport resembles cargo but becomes depth-restricted later. Capacity drops less quickly, and minimum loading fractions must be reduced at depths of about 3.3 metres. Its sensitivity lies between cargo and tankers.



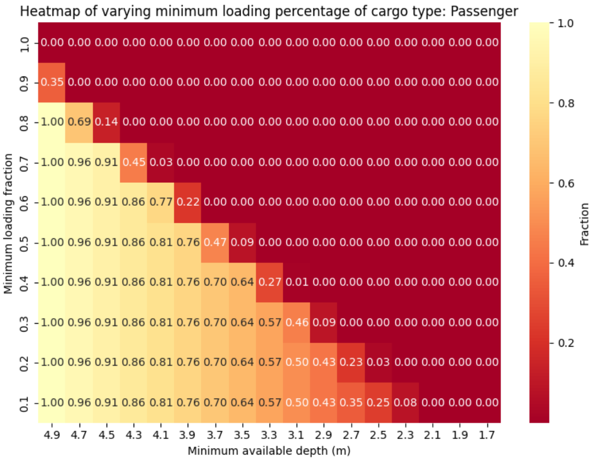
| Minimum loading fraction | 4.9 | 4.7 | 4.5 | 4.3 | 4.1 | 3.9 | 3.7 | 3.5 | 3.3 | 3.1 | 2.9 | 2.7 | 2.5 | 2.3 | 2.1 | 1.9 | 1.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.9 | 0.46 | 0.41 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.8 | 0.51 | 0.44 | 0.41 | 0.23 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.7 | 1.00 | 1.00 | 0.33 | 0.25 | 0.29 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.6 | 1.00 | 1.00 | 1.00 | 0.73 | 0.39 | 0.36 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.5 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.56 | 0.33 | 0.16 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.4 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 0.35 | 0.25 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.3 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 0.86 | 0.63 | 0.29 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.2 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 0.86 | 0.76 | 0.66 | 0.36 | 0.16 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.1 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 0.86 | 0.76 | 0.66 | 0.54 | 0.42 | 0.16 | 0.04 | 0.00 | 0.00 | 0.00 |
| 0.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 0.86 | 0.76 | 0.66 | 0.54 | 0.42 | 0.29 | 0.13 | 0.03 | 0.00 | 0.00 |

*Figure 48: Heatmap of simulation results, for varying the minimum loading percentage for the general cargo category.*



| Minimum loading fraction | 5.0 | 4.8 | 4.6 | 4.4 | 4.2 | 4.0 | 3.8 | 3.6 | 3.4 | 3.2 | 3.0 | 2.8 | 2.6 | 2.4 | 2.2 | 2.0 | 1.8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.9 | 0.77 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.8 | 0.77 | 0.74 | 0.44 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.7 | 0.77 | 0.74 | 0.70 | 0.54 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.6 | 0.77 | 0.74 | 0.70 | 0.66 | 0.62 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.5 | 0.77 | 0.74 | 0.70 | 0.66 | 0.62 | 0.57 | 0.30 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.4 | 0.77 | 0.74 | 0.70 | 0.66 | 0.62 | 0.57 | 0.52 | 0.35 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.3 | 1.00 | 0.78 | 0.70 | 0.66 | 0.62 | 0.57 | 0.52 | 0.46 | 0.40 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.2 | 1.00 | 0.94 | 0.88 | 0.70 | 0.62 | 0.57 | 0.52 | 0.46 | 0.40 | 0.33 | 0.15 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.1 | 1.00 | 0.94 | 0.88 | 0.81 | 0.74 | 0.61 | 0.52 | 0.46 | 0.40 | 0.33 | 0.26 | 0.13 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |

*Figure 49: Heatmap of simulation results, for varying the minimum loading percentage for the tanker category.*



| Minimum loading fraction | 4.9 | 4.7 | 4.5 | 4.3 | 4.1 | 3.9 | 3.7 | 3.5 | 3.3 | 3.1 | 2.9 | 2.7 | 2.5 | 2.3 | 2.1 | 1.9 | 1.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.9 | 0.35 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.8 | 1.00 | 0.69 | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.7 | 1.00 | 0.96 | 0.91 | 0.45 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.6 | 1.00 | 0.96 | 0.91 | 0.86 | 0.77 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.5 | 1.00 | 0.96 | 0.91 | 0.86 | 0.81 | 0.76 | 0.47 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.4 | 1.00 | 0.96 | 0.91 | 0.86 | 0.81 | 0.76 | 0.70 | 0.64 | 0.27 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.3 | 1.00 | 0.96 | 0.91 | 0.86 | 0.81 | 0.76 | 0.70 | 0.64 | 0.57 | 0.46 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.2 | 1.00 | 0.96 | 0.91 | 0.86 | 0.81 | 0.76 | 0.70 | 0.64 | 0.57 | 0.50 | 0.43 | 0.23 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.1 | 1.00 | 0.96 | 0.91 | 0.86 | 0.81 | 0.76 | 0.70 | 0.64 | 0.57 | 0.50 | 0.43 | 0.35 | 0.25 | 0.08 | 0.00 | 0.00 | 0.00 |

*Figure 50: Heatmap of simulation results, for varying the minimum loading percentage for the passenger category.*

**Varying seasonality:**

Figure 51, Figure 52 and Figure 53 show how seasonality and available depth affect system transport for the three different cargo types. The varying factor is the amplitude of the seasonal effects. At 0.0 seasonal effects, there are no seasonal effects and at a factor of 2 doubles the seasonal amplitude.

The heatmaps show that seasonality does not affect transport capacity for the most depth variations. Only around the restrictive depth of around 3.3-3m meters the seasonality will play a role. At first, the increased seasonality will reduce transport capacity because there are more months where no transport is possible. At lower average values the increased seasonality benefits transport capacity, because the large amplitude causes higher peak water levels, so more transport is possible in those peak months. Variations in seasonality measurement accuracy did not substantially affect the outcomes. So, no further investigation was required.

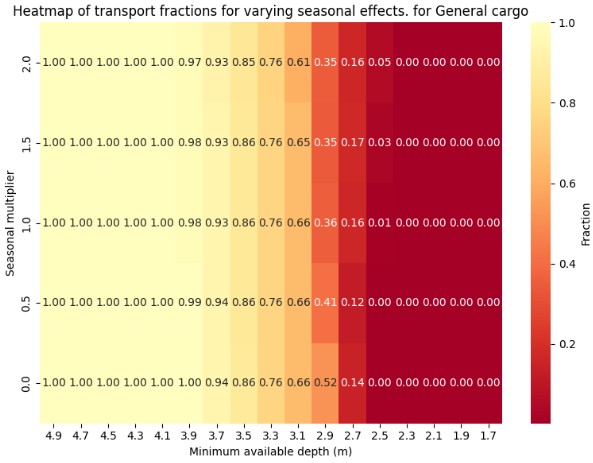


*Figure 51: Heatmap showing the effect of varying seasonal effects on transport capacity, for general cargo.*

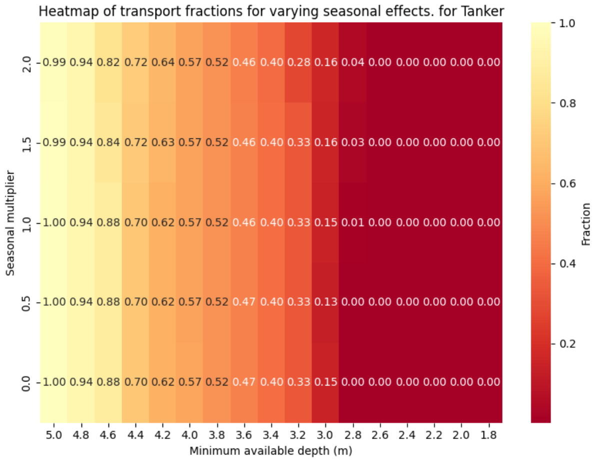


*Figure 52: Heatmap showing the effect of varying seasonal effects on transport capacity, for tankers.*

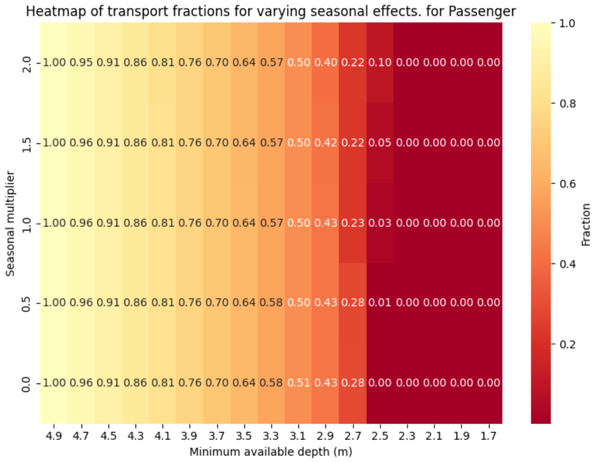


*Figure 53: Heatmap showing the effect of varying seasonal effects on transport capacity, for passenger cargo.*

### Vary (un) loading speed

Figure 54 shows how varying the (un)loading speeds at the ports influences transport capacity. The value on the y-axis is the multiplier that is used for the (un)loading speed of all vessels.

As expected, having twice the (un)loading rate results in more transport capacity, for all cargo types. The effect of faster (un)loading is mainly visible in the general Cargo type. Here the transport capacity increases to 1.76 as (un)loading speed double. The tanker and passenger category are at 1.3 and 1.25 respectively. These are still influenced by the changing speeds, but less than the general cargo. As there is less depth available, the differences between the results of changing speeds are starting to become less. At 2.9m water depth, all have fallen below 50% capacity, ranging between 13% and 42% for the base case and the most favourable case.

It turns out that changing (un)loading speeds will have effect at the water levels right now, but this effect diminishes as water level continue to fall.

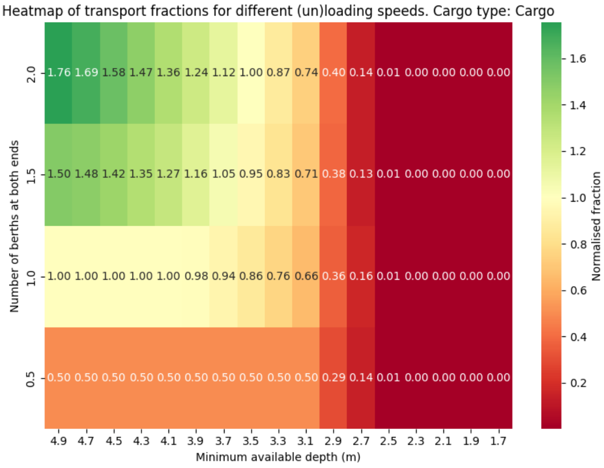


*Figure 54: Heatmap showing the effect of varying (un)loading speeds on transport capacity, for general cargo.*

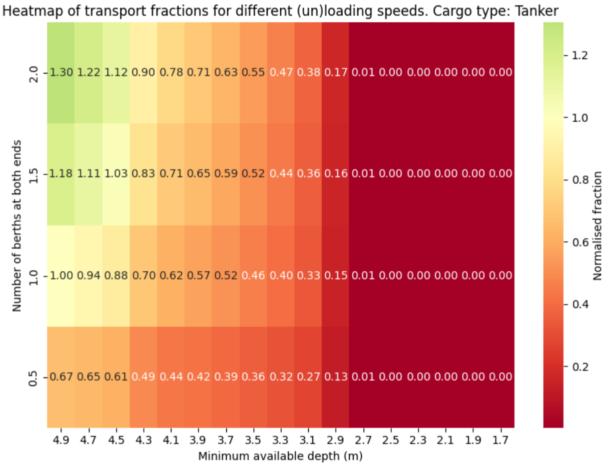


*Figure 55: Heatmap showing the effect of varying (un)loading speeds on transport capacity, for tankers.*

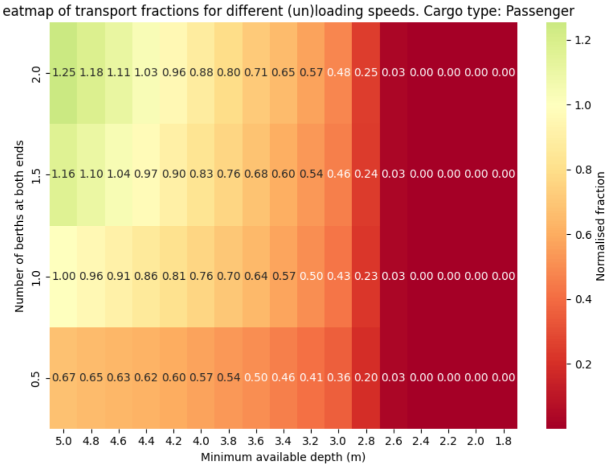


*Figure 56: Heatmap showing the effect of varying (un)loading speed on transport capacity, for passenger cargo.*

### Fleet composition:

shows the heatmap of varying the fleet. In this case only the base case and a 2x increase of these vessels is considered.

It turns out that doubling the number of vessels does not influence the general cargo category that much, this can be expected since the varying berths already showed that those are restricting transport capacity. So, more vessels will still run into the same issue.

Tanker and passenger transport will increase more by increasing their fleet. These go to 1.96 and 1.41 respectively. As water level fall for these categories, the transport capacity is still double that of the normal fleet. This shows that the vessels are not restricted by the number of berths or waiting time by (un)loading other vessels. So, doubling the number of vessels will increase transport even at lower water levels.

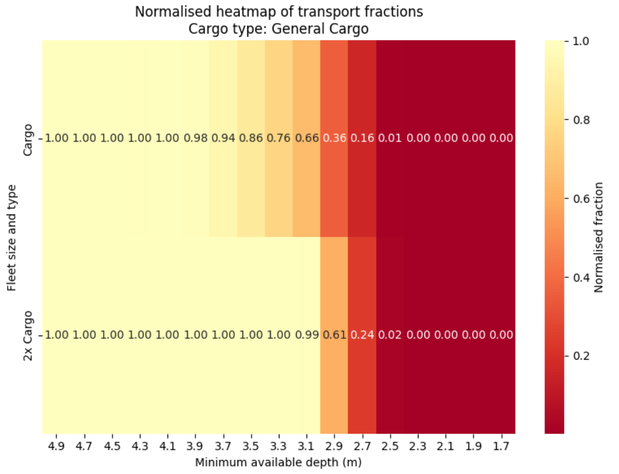


*Figure 57: Heatmap showing the effect of doubling the amount of vessel in a fleet on transport capacity for general cargo.*

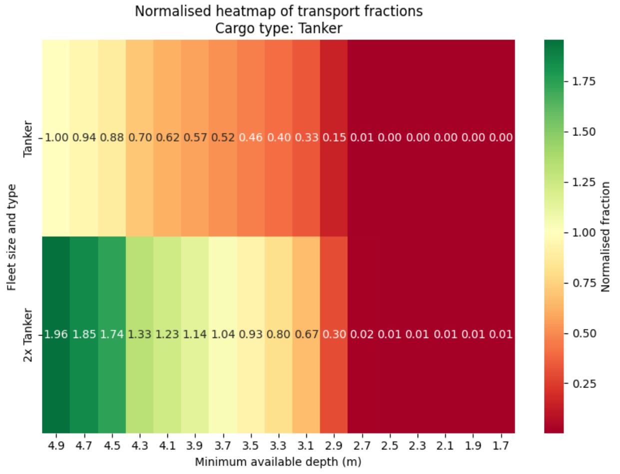


*Figure 58: Heatmap showing the effect of doubling the amount of vessel in a fleet on transport capacity for tanker transport.*

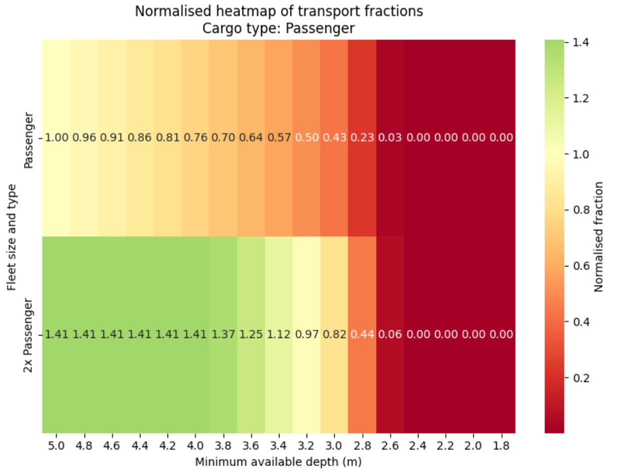


*Figure 59: Heatmap showing the effect of doubling the amount of vessel in a fleet on transport capacity for passenger cargo.*

### 4.3.2 Comparing parameter variations

To assess the sensitivity of the system with respect to depth, the sensitivity around the base case scenario, with an average depth of 5 metres, is evaluated for each cargo type. In addition, the sensitivity is calculated around the depth at which only 50% of the transport capacity remains in the base case as determined in 4.2.

Comparing these two conditions provides insight into which parameters are currently most influential and how their importance may change in the future. It should be noted that the favourable and unfavourable cases were selected based on informed estimates. Although they are reasonable, their exact accuracy cannot be guaranteed.

The choices for the varied parameters are shown below:

| | | Unfavourable | Base case | Favourable |
|---|---|---|---|---|
| Parameter: | Varies in | | | |
| Berths (both sides) | Berths | 1 | 1 or 2 | 4 |
| (UN)loading rate | % | 50 | 100 | 200 |
| Minimum loading percentage | % | 90 | 20 | 10 |
| Seasonality | % | 50 | 100 | 200 |
| Fleet | % | - | 100 | 100 |

*Table 6: Parameter variation for sensitivity analysis*

These variations led to the following results, show separately by cargo type:

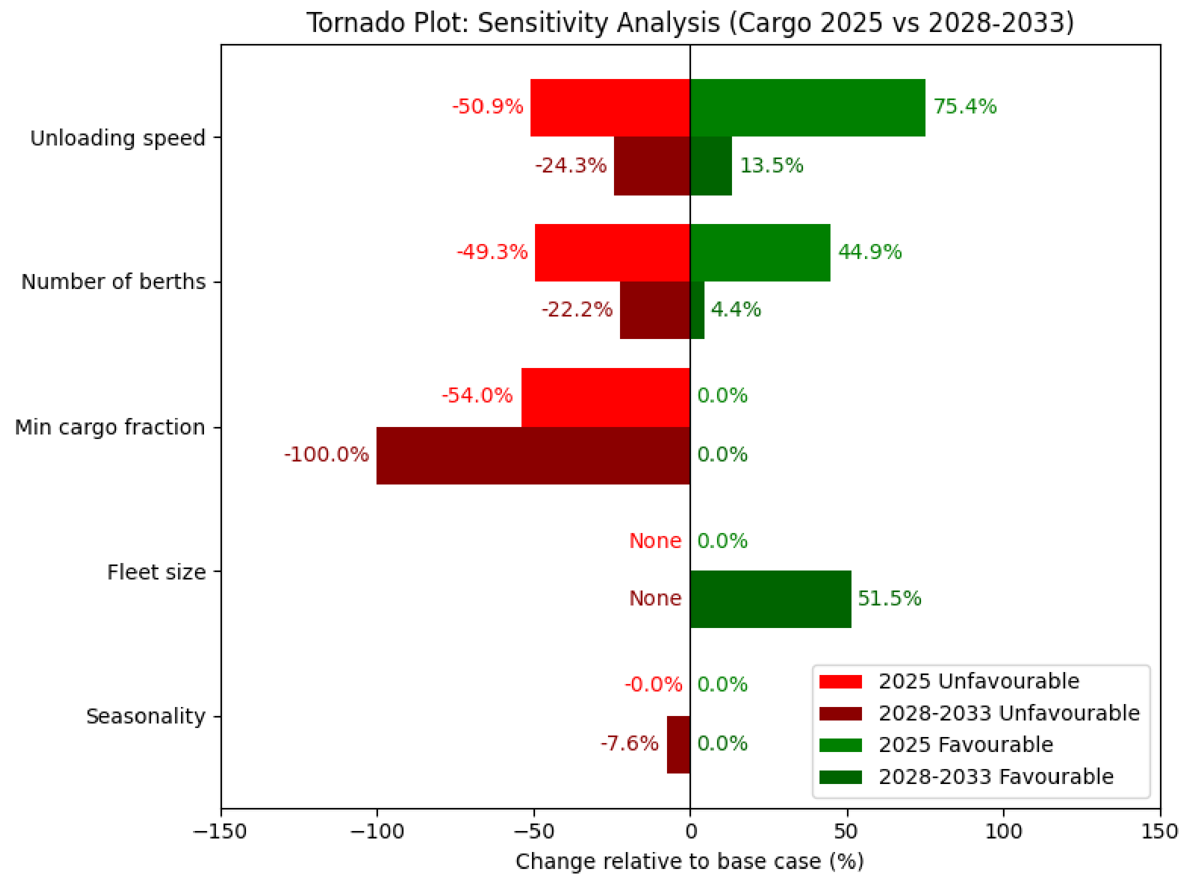


*Figure 60: Tornado plot for general cargo.*

Figure 60 shows the sensitivity of the system for different parameters and different depths. The green bars show the result of a favourable change in the parameter as defined in Table 6.

At the current depth in 2025, the (un)loading speed and number of berths are the most important if varied. This effect becomes less important as water levels fall. At lower water levels, the biggest positive impact on the system could be increasing the fleet size.

The largest negative impact comes from the minimum cargo fraction. This parameter is easily adjustable and will change with falling water levels.

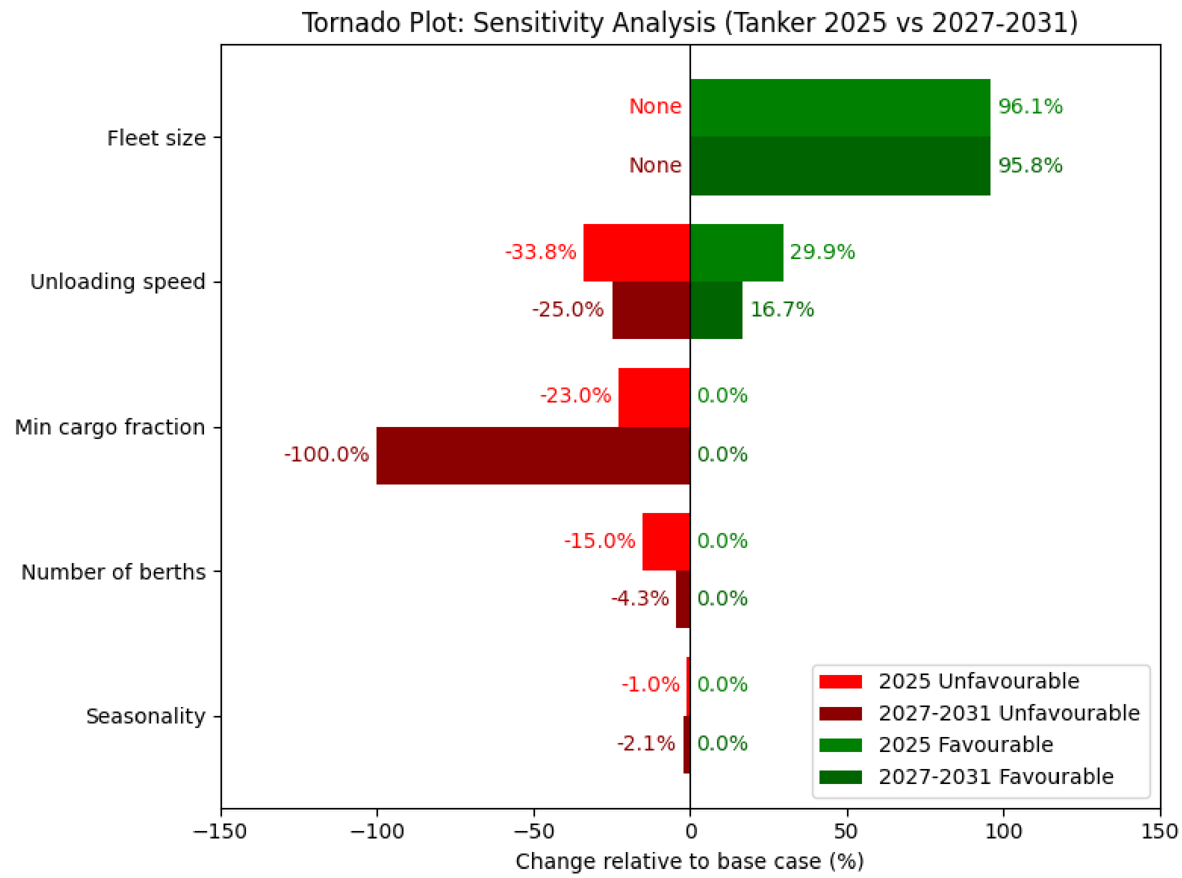


*Figure 61: Tornado plot for Tankers.*

Figure 61 shows the tornado plot for the Tanker category. Here the influence of Fleet size is large at all water levels. The number of berths can negatively impact the transport capacity for 15% and the unloading speed does affect the transport capacity between -34 and + 30 %. The effect of this becomes less as water levels fall.

The negative impact of the minimum cargo fraction becomes larger as water levels fall.

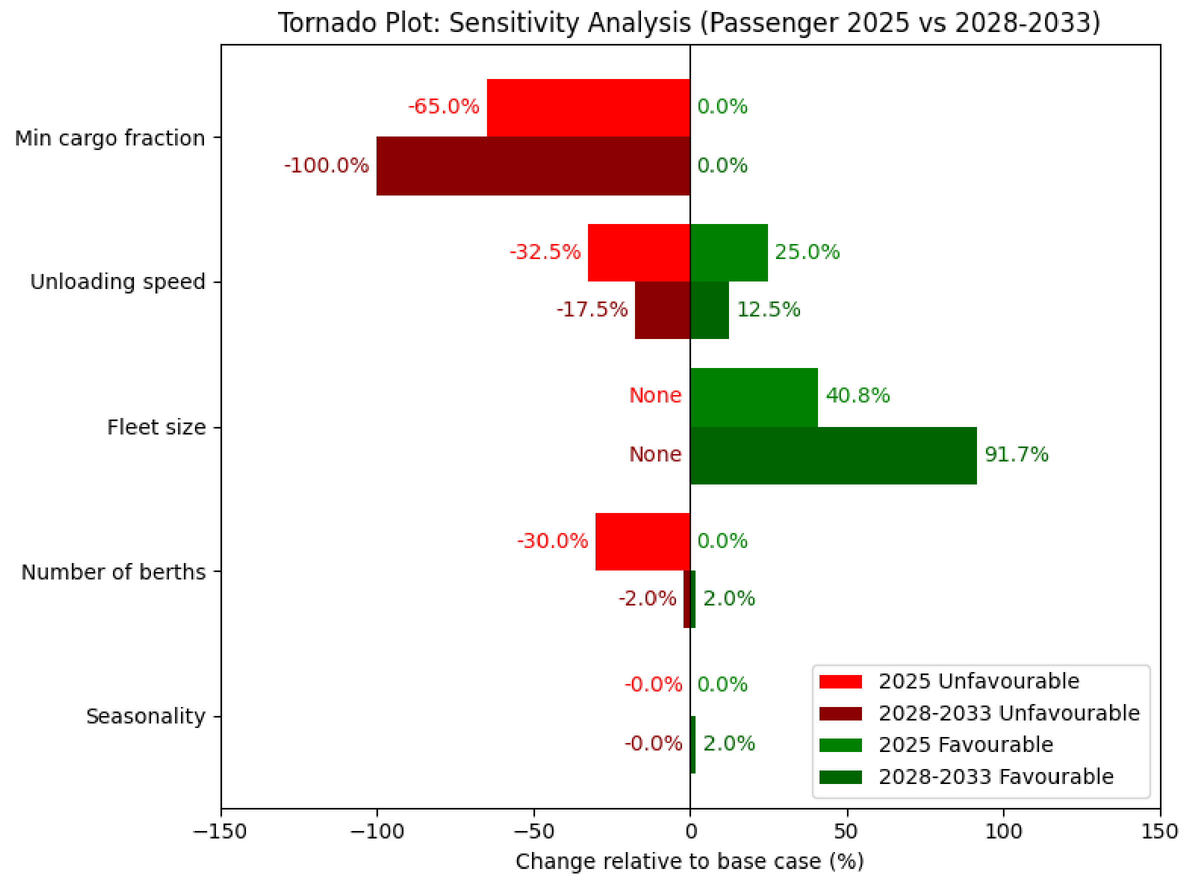


*Figure 62: Tornado plot for Passenger vessels.*

Figure 62 shows the tornado plot for Passenger vessels. Here the minimum cargo fraction can have the largest negative impact on total transports. Doubling the Fleet size will increase transports by 41% right now, but at lower water levels the relative increase will be more, at 92% increase.

All these figures show which parameters become more important in future scenarios.

# 5 Discussion, Conclusions and Recommendations

In this thesis a method was developed to quantify the performance of waterborne supply chains (that connect two harbours over sea) under changing climatic conditions. The method was applied to the case of the Caspian Sea. This chapter will discuss research limitations and significance, the conclusions and several recommendations.

## 5.1 Research limitations

Although this research provides meaningful insights into the impact of water level fluctuations on Caspian Sea transport routes, several limitations affect the scope of the findings. A more thorough examination of these limitations would enhance the accuracy of the results obtained through the proposed method, for other case studies:

- **Water level data**
  The study is limited by the availability and consistency of long-term water level data. Multiple, often conflicting, predictions for future Caspian Sea Levels make it difficult to link simulation results to specific future years with confidence.

- **Vessel data coverage**
  The total number of vessels was determined using open-source databases. However, there is no guarantee that the dataset is complete, and some relevant vessels may have been omitted, potentially impacting the accuracy of the transport capacity estimates.

- **Vessel parameters**
  Vessel draught values were primarily obtained from shipping company websites, where only fully loaded draughts are typically listed. Empty draughts had to be estimated based on similar vessel types, introducing uncertainty in the assessment of navigability under low water conditions.

- **Model assumptions**
  The model simulates cargo types separately and assumes independent use of access channels. In reality, all vessel types share the same navigational routes, which may result in underestimation of traffic congestion and associated delays when entering the port.

- **Sensitivity analysis method**
  A one-at-a-time (OAT) approach was used in the sensitivity analysis. This method does not capture potential interactions between parameters, which may underestimate the combined effects of multiple changes in the system.

- **Route-specific focus**
  The research focuses on two specific routes, Alat to Aktau and Alat to Kuryk, modelled as a single combined route. Other possible transport corridors in the Caspian region were not simulated, and port interactions outside these routes were not considered. Berth availability was adjusted indirectly based on assumptions, rather than modelled dynamically as part of a regional network.
- **Port development uncertainty**
  The three studied ports are undergoing ongoing expansion, with new terminals under construction. These developments may increase berth availability and significantly alter the future transport capacity, which is not reflected in the current model.
- **Cargo handling assumptions**
  The model assumes that handling time is determined solely by the total volume of loaded cargo, with no variation between cargo types. Unloading times are uniformly assumed to be shorter than loading times, which may not reflect operational realities at different terminals.
- **Weather conditions**
  The impact of weather, such as wind or wave conditions that can temporarily close ports or delay vessel movements, is not included in the model. These disruptions can play a significant role in the reliability of waterborne transport systems and will likely reduce transport capacity.
- **Policy**

  Restrictive policies can cause delays or inoperability. To get a more accurate result, local policy set up by the authorities should be taken into account.

## 5.2 Research significance

The model developed in this study holds significant potential for shipping companies seeking to understand the limitations of waterborne transport under changing water levels. While climate variability is increasingly recognised as a risk to maritime operations, there is still a notable gap in systematic analyses that directly link water level fluctuations to route-specific transport capacity.

By focusing on two key Caspian Sea routes, Aktau and Kuryk to Alat, this research provides insight onto how changing environmental conditions affect logistical performance. The findings contribute to identifying practical strategies for mitigating the decline in transport efficiency associated with falling water levels.

From a methodological standpoint, the study presents a framework that is transferable to other inland or regional water transport contexts. It enables the identification of navigational bottlenecks and highlights which parts of the transport system are most sensitive to hydrological change. This approach supports more resilient planning and investment decisions in the face of environmental uncertainty.

## 5.3 Conclusions

This section will show conclusions for each of the sub-questions. These will help to finally answer the main research question.

**Sub question 1**

*What are the physical and ship related factors that influence water transport performance?*

Waterborne transport performance depends on the interaction between waterway conditions and vessel characteristics. Among the physical aspects, water depth and long-term water level variability are the controlling factors, as they directly determine route accessibility and how much vessels can be loaded.

Ship-related characteristics determine how sensitive transport is to these physical limits. The draught and hull design of the available fleet define how much water depth is required for safe passage, while minimum loading thresholds constrain operational flexibility under shallow conditions. Capacity is further shaped by congestion at ports and regulatory restrictions, which may exacerbate the effects of limited depth.

For the Caspian Sea, depth-related constraints dominate. Declining water levels directly reduce accessibility to ports such as Kuryk and Aktau, where shallow access channels are the main factor reducing transport capacity. In this setting, depth is the decisive metric: once water levels drop below the draught requirements of large cargo vessels, capacity decreases sharply. The diversity of the fleet provides some resilience, as smaller vessels can still operate, but with less capacity. This means that in the Caspian, long-term water level change is the key driver of transport capacity, while ship characteristics determine how severe the reduction will be.

### Sub question 2

*How to locate potential bottlenecks due to changing water levels in a waterborne supply chain?*

Bottlenecks in waterborne supply chains occur when specific components of the system become restrictive to the overall flow of goods. Variations in water level can significantly affect the system's capacity and reliability. Identifying potential bottlenecks under these conditions requires a structured analysis that considers both physical and operational constraints.

Two primary types of bottlenecks can be distinguished:

**Navigational bottlenecks**
Navigational bottlenecks occur along the transport route and are directly related to the physical characteristics of the waterway. Falling water levels reduce the available depth, potentially rendering certain sections impassable. Long, shallow stretches are particularly vulnerable, as even minor decreases in water level can have large operational impacts, requiring extensive dredging. Low water levels may also affect port operations, for instance when a crane on a quay wall cannot reach cargo holds if the vessel lies too low in the water. Conversely, rising water levels can cause clearance issues under fixed infrastructure such as bridges, cables, or loading arms. In extreme cases, quay walls may flood, preventing (un)loading operations altogether. Navigational bottlenecks can be identified through bathymetric analysis and the assessment of port infrastructure.

**System parameter bottlenecks**
The system parameter bottlenecks arise from limitations within the transport system itself, such as port capacity, berth availability, minimum loading capacity, handling equipment, and fleet composition. Variability in water levels can reduce the load capacity of vessels, requiring more trips and time to move the same amount of cargo. This can result in congestion and increased waiting times. These bottlenecks can be identified by analysing vessel types, berth limitations, cargo handling requirements, and the total transport demand.

To systematically locate such bottlenecks, the following methodology is effective:

- Develop a base case simulation that accurately represents the current transport system.
- Vary key parameters one at a time while keeping other conditions constant.
- Quantify and compare the effect of each variation on system performance.

This approach enables the identification of current constraints as well as those that may emerge under different future water level scenarios. Recognising these critical points can support targeted interventions to increase the overall transport capacity of the system.

### Sub question 3

*What is the current performance of water transport, measured in total cargo volumes, in the Caspian Sea and how will it likely be affected by future sea level scenarios?*

Currently, water transport in the Caspian Sea is already constrained by water depth limitations in certain areas. The Middle Corridor route, which connects China to the European Union, transports approximately 3.4 million tonnes of cargo annually, and volumes have been increasing in recent years. Multiple countries are actively working to develop this corridor’s strategic potential.

Simulation of transport in section 4.2 between Alat and Kuryk/Aktau indicates that tanker transport will be the first to be significantly affected by declining water levels. This is primarily due to the relatively high draughts of tankers, which make them more vulnerable to depth restrictions. In the most optimistic scenario, characterised by strong climate mitigation efforts and reduced water extraction, tanker transport capacity falls to 50% by 2031. In the most pessimistic scenario, this occurs as early as 2027.

General cargo and passenger vessels are less sensitive to depth changes and are expected to reach 50% capacity between 2028 and 2033, depending on the rate of sea level decline. These projections assume that no additional dredging is carried out in the critical navigational bottleneck near Alat, where the long access channel becomes increasingly shallow under future scenarios.

### Sub question 4

*What are possible solutions for water transport where water levels are expected to fall, applied to the Caspian Sea?*

The results of the sensitivity analysis in section 4.3 have shown that several strategies can effectively mitigate the negative effects of falling water levels on water transport across the Caspian Sea. The most critical solution, based on the tornado plots, is to allow vessels, especially general cargo ships, to operate with lower minimum cargo loading fractions. As depth decreases, maintaining a low minimum cargo requirement becomes increasingly important to keep vessels operational and avoid capacity losses. Flexible operational rules that permit less loaded vessels can therefore extend the viability of shipping in low depth scenarios.

Improving port infrastructure is another important solution. For general cargo vessels, the addition of a third berth at the ports was found to significantly increase transport capacity under current conditions. However, at lower water levels, the benefits of adding more berths diminish. Therefore, infrastructure investments should be carefully prioritised, focusing on ensuring operational flexibility rather than simply expanding capacity.

Enhancing (un)loading speeds also offers an effective strategy to maintain transport capacity. Faster loading and unloading significantly benefit general cargo vessels and to a lesser extent tanker and passenger ships. Investments in port equipment, logistics efficiency, and staff training could help reduce turnaround times and thereby offset some of the capacity losses linked to reduced vessel draught.

Lastly, maintaining or modestly expanding the size of the vessel fleet could help to balance transport demands when individual vessel capacity declines. The sensitivity analysis also shows that increasing the fleet size is the only adjustment that does not see diminishing returns as water levels fall.

In summary, increasing fleet size, ensuring flexible loading requirements, improving (un)loading speeds, and targeted port upgrades are the most effective solutions for sustaining water transport on the Caspian Sea as water levels fall. A combination of increasing berths and total fleet will probably ensure the most transport growth. To calculate this potential transport increase, changes can be made to the base case and then compared to the current base case. These strategies will be essential to preserve the economic and logistical functionality of shipping routes in the region under future low-water conditions.

**Research question:**

*How do waterborne supply chains react to changing water levels with an application to the Caspian Sea?*

This research combined simulation of water level changes with analysis of port and vessel operational constraints to assess their impact on waterborne supply chains in the Caspian Sea. The methodology focused on determining transport capacity for varying water levels and system parameters such as fleet size, number of berths, (un)loading speed, minimum loading capacity and seasonal effects. The method allows to determine the impact of these system parameters at all water levels, so it becomes possible to determine which parameters become more and less important as water levels fall.

The general findings show that waterborne supply chains in the Caspian Sea are highly sensitive to water level fluctuations. Declining levels directly reduce port accessibility and limit vessel size, leading to significant decreases in transport capacity. Between 2027 and 2033 capacity reductions of up to 50% are expected for several cargo types. Lower water levels are also likely to force vessels to transport less cargo per trip, which increases costs and delays, resulting in less transport demand.

More detailed analysis in section 4.3 highlights that navigational bottlenecks are likely to develop along the Alat–Kuryk/Aktau route, particularly in the shallow 5-kilometre access channel at Alat. To maintain accessibility, substantial dredging will be required. In the short term, strategies such as adding berths or improving (un)loading speed could help sustain throughput. In the long term, however, expanding the fleet is expected to be the most effective option for maintaining transport capacity under declining water levels.

The method helped determine that in the base case scenario of the Alat- Kuryk/Aktau route the general cargo transport is restricted by the number of berths and the tanker and passenger category by the number of vessels. This will help determine which investments can be done to improve all three categories.

Since ports along the route are already developing new terminals, their infrastructure is expected to remain adequate provided that dredging and regular upgrades continue. Nevertheless, adaptability remains essential: ports must adjust dredging schedules and invest in facilities capable of coping with both lower water levels and increasing cargo demand.

## 5.4 Recommendations

The methodology developed in this thesis provides a structured way to assess how waterborne supply chains respond to changing water levels. Based on the outcomes and limitations identified, the following methodological recommendations are made:

- **Broaden application to other routes and contexts**
  The approach used here, combining bottleneck identification with simulation and sensitivity analysis, should be applied to other Caspian routes and inland waterways. This would test its generalisability and provide insights into different regional vulnerabilities.

- **Advance sensitivity analysis techniques**
  This thesis used a one-at-a-time (OAT) sensitivity approach. Expanding to multi-parameter or probabilistic sensitivity analysis would allow for better assessment of interactions between variables such as fleet size, berth availability, and water depth.

- **Improve input data quality**

  It should be noted that the fleet and its vessel specifications should be more accurate for better results. The fleet in this case study was estimated by reviewing AIS data of previous vessels that made the trip. In the case vessels are not always route specific, and the routes they sail are determined by demand.

- **Integration with broader supply chain models**
  Since this study focused only on port-to-port capacity, future extensions could include total port operations. For this method the berths of a port are dedicated to a certain route. Adding traffic from other routes would results in more varying berth availability and a more accurate simulation.

# Table of figures

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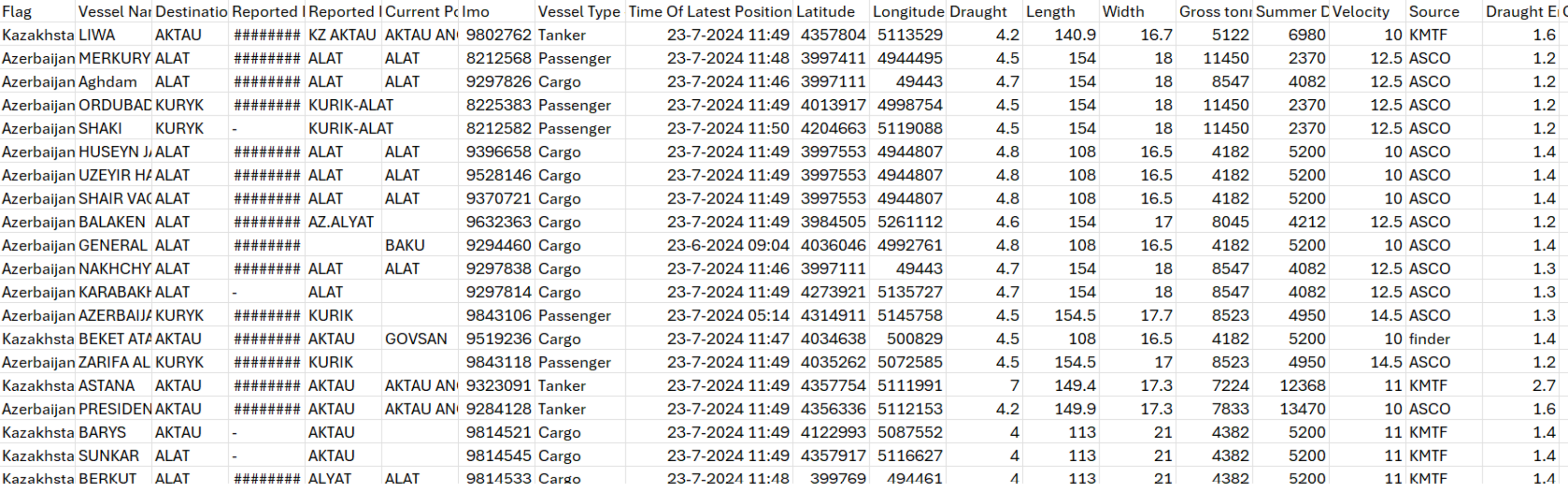
# Appendix A

Table of all vessels used:



| Flag | Vessel Na | Destinatio | Reported | Reported | Current P | Imo | Vessel Type | Time Of Latest Position | Latitude | Longitude | Draught | Length | Width | Gross ton | Summer D | Velocity | Source | Draught E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kazakhsta | LIWA | AKTAU | ######## | KZ AKTAU | AKTAU AN | 9802762 | Tanker | 23-7-2024 11:49 | 4357804 | 5113529 | 4.2 | 140.9 | 16.7 | 5122 | 6980 | 10 | KMTF | 1.6 |
| Azerbaijan | MERKURY | ALAT | ######## | ALAT | ALAT | 8212568 | Passenger | 23-7-2024 11:48 | 3997411 | 4944495 | 4.5 | 154 | 18 | 11450 | 2370 | 12.5 | ASCO | 1.2 |
| Azerbaijan | Aghdam | ALAT | ######## | ALAT | ALAT | 9297826 | Cargo | 23-7-2024 11:46 | 3997111 | 49443 | 4.7 | 154 | 18 | 8547 | 4082 | 12.5 | ASCO | 1.2 |
| Azerbaijan | ORDUBAD | KURYK | ######## | KURIK-ALAT |  | 8225383 | Passenger | 23-7-2024 11:49 | 4013917 | 4998754 | 4.5 | 154 | 18 | 11450 | 2370 | 12.5 | ASCO | 1.2 |
| Azerbaijan | SHAKI | KURYK | - | KURIK-ALAT |  | 8212582 | Passenger | 23-7-2024 11:50 | 4204663 | 5119088 | 4.5 | 154 | 18 | 11450 | 2370 | 12.5 | ASCO | 1.2 |
| Azerbaijan | HUSEYN J | ALAT | ######## | ALAT | ALAT | 9396658 | Cargo | 23-7-2024 11:49 | 3997553 | 4944807 | 4.8 | 108 | 16.5 | 4182 | 5200 | 10 | ASCO | 1.4 |
| Azerbaijan | UZEYIR H | ALAT | ######## | ALAT | ALAT | 9528146 | Cargo | 23-7-2024 11:49 | 3997553 | 4944807 | 4.8 | 108 | 16.5 | 4182 | 5200 | 10 | ASCO | 1.4 |
| Azerbaijan | SHAIR VA | ALAT | ######## | ALAT | ALAT | 9370721 | Cargo | 23-7-2024 11:49 | 3997553 | 4944807 | 4.8 | 108 | 16.5 | 4182 | 5200 | 10 | ASCO | 1.4 |
| Azerbaijan | BALAKEN | ALAT | ######## | AZ.ALYAT |  | 9632363 | Cargo | 23-7-2024 11:49 | 3984505 | 5261112 | 4.6 | 154 | 17 | 8045 | 4212 | 12.5 | ASCO | 1.2 |
| Azerbaijan | GENERAL | ALAT | ######## |  | BAKU | 9294460 | Cargo | 23-6-2024 09:04 | 4036046 | 4992761 | 4.8 | 108 | 16.5 | 4182 | 5200 | 10 | ASCO | 1.4 |
| Azerbaijan | NAKHCHY | ALAT | ######## | ALAT | ALAT | 9297838 | Cargo | 23-7-2024 11:46 | 3997111 | 49443 | 4.7 | 154 | 18 | 8547 | 4082 | 12.5 | ASCO | 1.3 |
| Azerbaijan | KARABAK | ALAT | - | ALAT |  | 9297814 | Cargo | 23-7-2024 11:49 | 4273921 | 5135727 | 4.7 | 154 | 18 | 8547 | 4082 | 12.5 | ASCO | 1.3 |
| Azerbaijan | AZERBAIJ | KURYK | ######## | KURIK |  | 9843106 | Passenger | 23-7-2024 05:14 | 4314911 | 5145758 | 4.5 | 154.5 | 17.7 | 8523 | 4950 | 14.5 | ASCO | 1.3 |
| Kazakhsta | BEKET AT | AKTAU | ######## | AKTAU | GOVSAN | 9519236 | Cargo | 23-7-2024 11:47 | 4034638 | 500829 | 4.5 | 108 | 16.5 | 4182 | 5200 | 10 | finder | 1.4 |
| Azerbaijan | ZARIFA AL | KURYK | ######## | KURIK |  | 9843118 | Passenger | 23-7-2024 11:49 | 4035262 | 5072585 | 4.5 | 154.5 | 17 | 8523 | 4950 | 14.5 | ASCO | 1.2 |
| Kazakhsta | ASTANA | AKTAU | ######## | AKTAU | AKTAU AN | 9323091 | Tanker | 23-7-2024 11:49 | 4357754 | 5111991 | 7 | 149.4 | 17.3 | 7224 | 12368 | 11 | KMTF | 2.7 |
| Azerbaijan | PRESIDEN | AKTAU | ######## | AKTAU | AKTAU AN | 9284128 | Tanker | 23-7-2024 11:49 | 4356336 | 5112153 | 4.2 | 149.9 | 17.3 | 7833 | 13470 | 10 | ASCO | 1.6 |
| Kazakhsta | BARYS | AKTAU | - | AKTAU |  | 9814521 | Cargo | 23-7-2024 11:49 | 4122993 | 5087552 | 4 | 113 | 21 | 4382 | 5200 | 11 | KMTF | 1.4 |
| Kazakhsta | SUNKAR | ALAT | - | AKTAU |  | 9814545 | Cargo | 23-7-2024 11:49 | 4357917 | 5116627 | 4 | 113 | 21 | 4382 | 5200 | 11 | KMTF | 1.4 |
| Kazakhsta | BERKUT | ALAT | ######## | ALYAT | ALAT | 9814533 | Cargo | 23-7-2024 11:48 | 399769 | 494461 | 4 | 113 | 21 | 4382 | 5200 | 11 | KMTF | 1.4 |