Reducing maintenance dredging at the Eemshaven harbor

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SUMMARY

Harbors around the world have to deal with the unwanted deposition of sediment (siltation) in its basins and fairways. To keep the harbor and its access routes accessible for marine activities, annual maintenance dredging operations are executed. At the Eemshaven harbor for example, which is situated in the Ems estuary, approximately 1,5 million m^3 of dredge is removed every year. This practice is very expensive, can have negative effects on the environment and does not address the source of the problem. Therefore, this study investigates possible measures which can limit the necessity for maintenance dredging.

First, the most important natural factors shaping the sediment dynamics throughout the Ems estuary are analyzed. Additionally, the mechanisms shaping the siltation rate at the Eemshaven harbor are described. Then, based on previous physical and numerical modelling, and actual implementations of siltation reduction measures in comparable harbors as described in literature, there are three promising measures which can reduce the necessity for maintenance dredging at the Eemshaven harbor. First, a Current Deflection Wall results in a decrease in siltation between 15 and 22%. Furthermore, combining the CDW with a sill leads to a siltation reduction between 18 and 55%. Additionally, pile groynes leads to a reduction of 53%. Lastly, the Passive Nautical Depth method leads to a reduction in siltation of 10% and an Active Nautical Depth can result in a 100% reduction.

This study advices that a follow-up modelling research prepares different scenarios with different combinations and configurations of a CDW, CDW and sill, and pile groynes in order to analyze the effectiveness in terms of siltation reduction. Additionally, in-depth analysis of the physical properties of the mud in the Eemshaven are vital to assess whether the Nautical Depth method can be applied. The modelling research can use the qualitative data on the estuarine environment as presented in this research as input, validation, and calibration of the model.

SAMENVATTING

Havens over de hele wereld hebben te maken met de ongewenste afzetting van sediment (aanslibbing) in hun toegangsvaargeulen en bassins. Om de haven en de toegangsroutes toegankelijk te houden voor maritieme activiteiten worden jaarlijks onderhouds baggerwerkzaamheden uitgevoerd. Zo wordt bij de Eemshaven, gelegen in het Eems-estuarium, jaarlijks circa 1,5 miljoen m^3 bagger verwijderd. Echter, dit is duur, kan negatieve gevolgen hebben voor het milieu en lost de oorzaak van het probleem niet op. Daarom wordt in dit onderzoek mogelijke maatregelen onderzocht die de noodzaak van deze baggerwerkzaamheden kunnen verminderen.

Eerst worden de belangrijkste natuurlijke factoren die de sediment dynamiek in het Eems-estuarium bepalen kwalitatief geanalyseerd. Daarnaast worden de mechanismen beschreven die zorgen voor de aanslibbing in de Eemshaven. Vervolgens worden er drie kansrijke maatregelen die de noodzaak van onderhoudsbaggeren in de Eemshaven kunnen verminderen geselecteerd op basis van voorgaande fysieke en numerieke modellering en daadwerkelijke implementaties van slibbeperkende maatregelen in vergelijkbare havens zoals beschreven in de literatuur. Ten eerste resulteert een Current Deflection Wall (CDW) in een afname van de aanslibbing tussen 15% en 22%. Bovendien leidt het combineren van de CDW met een drempel tot een reductie tussen de 18% en 55%. Daarnaast leidt een palen-rij tot een reductie van 53%. Ten slotte leidt de Passive Nautical Depth-methode tot een reductie van 10% en een Active Nautical Depth kan zelfs resulteren in een reductie van 100%.

Deze studie adviseert dat een vervolgmodelleringsonderzoek verschillende scenario's voorbereidt met verschillende combinaties en configuraties van een CDW, CDW en drempel en een palen-rij om de effectiviteit in termen van reductie in aanslibbing te analyseren. Daarnaast is een diepgaande analyse van de fysische eigenschappen van de modder in de Eemshaven essentieel om te beoordelen of de Nautische Dieptemethode toepasbaar en effectief kan zijn. Het modelonderzoek kan de kwalitatieve gegevens over het Eems estuarium zoals gepresenteerd in dit onderzoek gebruiken als input, validatie en kalibratie van het model.

LIST OF ABBREVIATIONS

Symbol	Meaning
F_s	Siltation rate
p	Trapping efficiency of a harbor
c_a	Sediment concentration outside the harbor
Q	Rate of water exchange between a harbor and surrounding water
Q_t	Rate of water exchange due to tidal filling
a	Tidal amplitude
S	Surface area of the harbor basin
T	Tidal period
Q_d	Rate of water exchange due to density driven currents
f_d	Exchange coefficient of water exchange due to density driven currents
A	Cross section area of the harbor entrance
$\Delta\rho_m$	Density difference between surrounding water and harbor at the harbor entrance during a tidal cycle
ρ	Density of salt
g	Gravitational constant
h_0	Mean water depth at harbor entrance
$f_{t,d}$	Exchange coefficient of water exchange reflecting the temporal variation and difference between the tides and salinity of the water
f_e	Exchange coefficient of water exchange due to horizontal entrainment
u_r	River flow velocity
Q_e	Rate of water exchange due to horizontal entrainment (turbulent mixing layer)

1. INTRODUCTION

In the North of the Netherlands lies the Wadden Sea. In 2009, the Wadden Sea was added to UNESCO's World Heritage List due to the fact that the biodiversity around the world depends on this area and it has "the largest tidal flat system in the world, where natural processes proceed largely undisturbed" (Common Wadden Sea Secretariat, n.d.). Within the Wadden Sea area, on the border with Germany, lies the Ems estuary as shown in Figure 1 below. An estuary is "a semi-enclosed coastal body of water, which has a free connection with the open sea, and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard, 1967). The open sea connection is at the area between Borkum and Rottumeroog and the freshwater inflow mostly comes from the Ems river situated near Emden (Baptist & Philippart, 2015). The estuary plays an important role in providing and circulating nutrients for the numerous organisms present there such as bacteria, algae, shell-fish, fish, birds, plankton, and sea-mammals (Bos et al., 2012; Taal et al., 2015). Furthermore, it is a migration route and feeding area for numerous species including species which are specifically adapted to its environment (Schuchardt & Scholle, 2017). Approximately 2000 seals and tens of thousands of migrating birds touch down in the Ems estuary specifically (Litjens et al., 2013). Thus, the estuary houses a complex food-chain and a multitude of organisms. In addition to the ecological value of the estuary, there are significant economic actors present as well. The harbors of Eemshaven, Delfzijl and Emden and "one of the world's biggest shipyards for ocean cruisers" (Baptist & Philippart, 2015) at Papenburg depend heavily on the estuary for the passage of their ships. Figure 1 below shows the location of the harbors within the estuary.

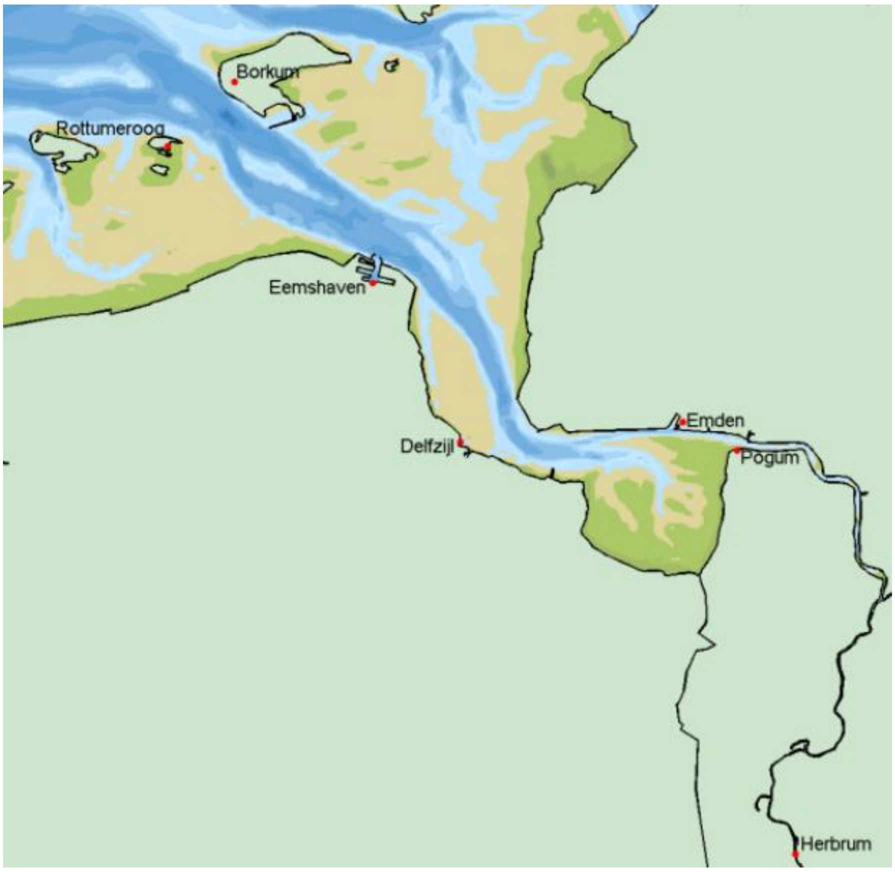


Figure 1: Overview of the Ems estuary showing the inlet at the North Sea at Rottumeroog and Borkum, the harbors of Eemshaven, Delfzijl, and Emden and a part of the Ems river until Herbrum where the tidal influence ends due to a man-made dam. Figure taken and adapted from Grasmeijer & Pasmans (2013).

Problem Definition

However, the presence of these harbors and other anthropogenic interventions in the estuary have affected the natural system significantly. Numerous research has shown that the construction of the dam at Herbrum, the historic deepening and widening of channels in the estuary and the Ems river to accommodate more and larger ships (Talke & De Swart, 2006) and the expansion of harbors has had large consequences on the ecology, morphology, hydrodynamics and sediment transport in the estuary (Bos et al., 2012; Spiteri et al., 2011; Talke & de Swart, 2006; Litjens et al., 2013; Van Duren, 2011; Rijkswaterstaat, 2018). Furthermore, the dredging activities of the harbors arguably have negative effects on the environment as well (Bianchini et al., 2019; Ecologie en Economie in Balans, 2014; Baptist et al., 2007; Sharp et al., 2010). The necessity for dredging is a result of the location of a harbor. The location of harbors in general is chosen such that they provide safe and efficient access for ships (Huguet et al., 2020; Kirby, 2013). However, this choice of location invariably results in the deposition of sediment as this is also an environment where sediment can settle quite efficiently (Huguet et al., 2020). This settling of sediment in a harbor is called siltation and it inhibits the access of ships toward and into a harbor, thereby negatively impacting the economic activity surrounding a harbor (Talke & de Swart, 2006; Bianchini et al., 2019; Kirby, 2013). Therefore, there exists an ongoing necessity for harbors around the world to remove these settled sediments. The traditional and most widely used method to remove this is by dredging (Bianchini et al., 2019). However, this is generally very costly, has an ever recurring cycle as it does not tackle the source of the siltation (Bianchini et al., 2019), and arguable leads to an increase in suspended sediment concentration (Bos et al., 2012; Van Maren et al., 2015). Even though sediment is vital for the “food cycles and the dynamics of water quality” (Bianchini et al., 2019) and estuaries are naturally slightly turbid, having a certain natural suspended sediment concentration, the Ems estuary has become “hyperturbid” (Baptist & Philippart, 2015) in certain areas. This situation affects fish and shellfish as sediment can block their filtration system (Bos et al., 2012) and also leads to lower irradiation levels in the water which can result in a decreased primary production of phytoplankton (Baptist & Philippart, 2015; Litjens et al., 2013). Taal et al. (2015) explain that the food produced by these phytoplankton are at the basis of the food-chain and can therefore have large ecological consequences.

Aim of study

Therefore, reducing the necessity for traditional maintenance dredging in the estuary can be beneficial for both the health of the estuary and for the harbor companies. In order to achieve this, Kirby (2011), PIANC (2008), Baptist et al. (2007), and the European Sediment Research Network (2004) all argue that a thorough understanding of the processes which transport the sediment within the estuary and towards a harbor should be at the basis of any such research. Therefore, this research outlines and connects previous research on the Ems estuarine system and possible ways to minimize maintenance dredging in harbors. This will form the basis for a follow-up modelling research.

2. RESEARCH QUESTIONS

Consequently, the following main question and the subsequent sub-questions are answered in this research.

Main question:

What can be effective measures to reduce maintenance dredging at the Eemshaven harbor?

Sub-questions:

1. Which physical processes determine the sediment dynamics in the Ems estuary?
2. Which physical processes determine the sediment deposition rate (siltation) in a harbor and specifically at Eemshaven?
3. Which siltation reduction measures are reported in the literature?

The current research provides the basis for a follow-up modelling research. The knowledge and qualitative data of the sediment dynamics in the estuary and around the harbor of Eemshaven as obtained in sub-questions 1 and 2 can be used to model the effectiveness of siltation reduction measures as found and analyzed in sub-question 3.

3. METHODS

This study focuses on measures which reduce siltation at the Eemshaven harbor in order to reduce the necessity of maintenance dredging in the harbor basins. To be able to analyze the effectiveness of these measures, the sediment dynamics in the estuary and into and around the port of Eemshaven must be understood. Groningen Seaports and Rijkswaterstaat are responsible for the dredging in the harbors and fairways around the Ems estuary respectively. The choice of Eemshaven is made in collaboration with Groningen Seaports. They communicated that no specific research has been done as of yet into siltation reduction measures at this harbor. Therefore, this provides a unique opportunity to fill that research gap. This study therefore focuses on the relevant mechanisms for the Eemshaven harbor specifically.

The research questions are answered using a combination of literature research and frequent feedback sessions with Joop van Dijken from Groningen Seaports and dr. Alex Kirichek who is an expert in this field working at Deltares and the TU Delft. Sub-question 1 is answered in chapter 5 by qualitatively analyzing the physical processes in the estuary as a whole and near the Eemshaven harbor-estuary interface specifically as described in the literature. Sub-question 2 is answered in chapter 6 by qualitatively analyzing the exchange mechanisms between the Eemshaven and the estuary. This is done by using the qualitative data found in chapter 5 and the relevant physical data provided by Groningen Seaports and from literature. Sub-question 3 is answered in chapter 7 by analyzing the appropriate siltation reduction measures described in literature. The selection of these measures from literature are made based on similarity in harbor configuration and local environment. Based on this literature research, some propositions for possible designs are presented as well. These designs can be used a basis for a follow-up modelling research.

System boundary

The dredging of the fairways, as done by Rijkswaterstaat in the Netherlands and WSA in Germany (Van Dijken, 2020) are outside of the scope. Only the dredging of the Eemshaven harbor specifically is taken into account. Additionally, the effect of ship traffic around the Eemshaven on the sediment-and hydrodynamics is not taken into account. Furthermore, based on PIANC (2008), episodic events such as floods and storms which can have an influence on siltation rates are not included as it is difficult to both value their contribution to siltation and also on how to mitigate their effect (PIANC, 2008). Additionally, financial and environmental aspects are not taken into account.

4. SYSTEM ANALYSIS

The Ems estuary is typically subdivided into four areas: the “outer area … the inner area … the Dollard, and the Ems River” (Spiteri et al., 2011). This distinction is based on the different physical characteristics and dominant physical processes in each area (Spiteri et al., 2011). According to Bos et al. (2012), an estuary has a marine section with direct connection to the sea, an area with a salt-sweet water mixture, and a fluvial section dominated by freshwater but still under influence of the tides. Usually, the estuary is defined as the area between Borkum and Herbrum at which the tidal influence ends due to a man-made dam, see figure 1 (Spiteri et al., 2011; Baptist & Philippart, 2015). Within the estuary, tidal- and wind-induced waves and currents together with fresh water inflow from the Ems river interact with an immensely diverse geographic morphology as it flows through the estuary. This morphology ranges from deep and shallow sections, mud- and sandflats, to numerous channels (Bos et al., 2012).

The maintenance of the harbors in Delfzijl and Eemshaven which include the dredging activities and the industrial sites, is the responsibility of Groningen Seaports. To get an impression of the size and layout of the Eemshaven harbor, an aerial view is shown in Figure 2 below. The entrance of the harbor is at the top left corner and the individual basins can be seen together with some of the industrial sites settled there.

Figure 2: Aerial view of the Eemshaven harbor. Picture taken by Boertjens, K (n.d.).

Additionally, a top-view illustration of the Eemshaven harbor is given in Figure 3 below. The harbor mouth of the Eemshaven has breakwaters which create a tranquil environment for accessible navigability. Additionally, the harbor consists of four separate harbor basins, Beatrixhaven, Julianahaven, Emmahaven and Wilhelminahaven, and one main channel, the Doekegatkanaal (Groningen Seaports, 2020). The entrance width of the Doekegatkanaal is 470 meters which narrows to 325 meters at the intersection with the Beatrixhaven. The width at the bottom of the channel is 200 meters and the length of the channel is 2100 meters (Groningen Seaports, 2020).

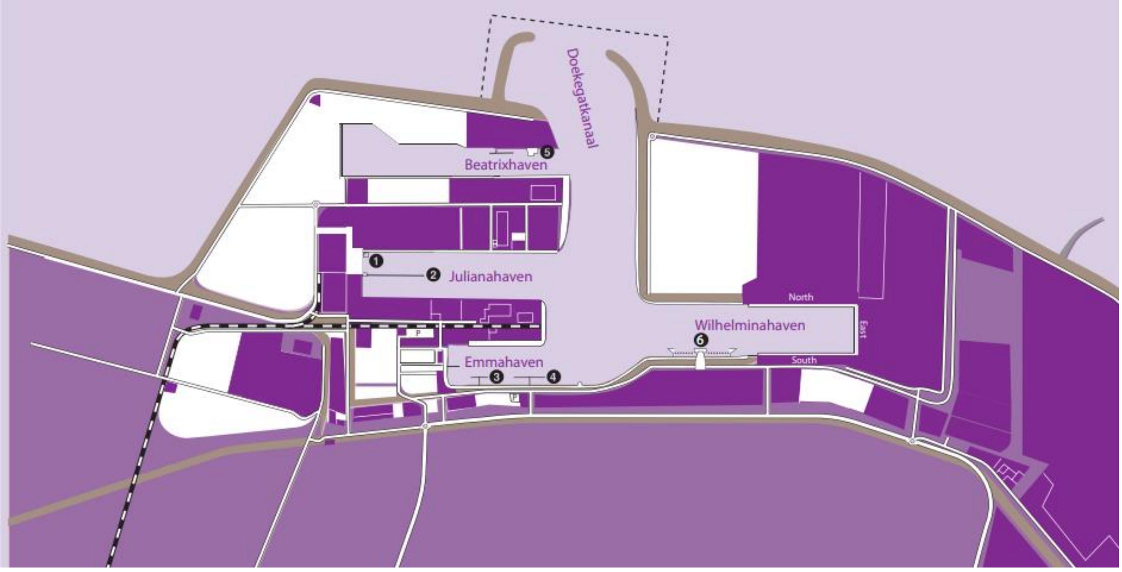


Figure 3: Overview of the Eemshaven harbor. The Beatrix-, Juliana-, Emma-, and Wilhelminabasins and the main channel called the Doekegatkanaal are illustrated. Taken from Groningen Seaports (2020).

The channel and basins must be kept at a minimal maintenance and navigational depth (Van Dijken, 2020). This is currently done by traditional dredging where a ship, a so-called trailing suction hopper, is used (Maritiem Nederland, 2019). There are two dredging campaigns annually which last five weeks in total (Van Dijken, 2020). Between March and October, depositing dredge is prohibited as the turbidity in the estuary should be kept at a minimum (Van Dijken, 2020). Therefore, the first campaign occurs in February and the second at the end of October or beginning of November (Van Dijken, 2020). In 2019, a total of 1.6 million m^3 of dredge has been removed from the Eemshaven harbor and nearly 70% of this comes from the Doekegatkanaal (Van Dijken, 2020).

The depths which must be maintained in each of the basins and the main channel are given in table 1 below. The Maintenance Depth is the depth which must be achieved by the dredging companies when they dredge in order to guarantee the Nautical Guaranteed Depth until the next dredging campaign due to the fact that siltation occurs throughout the year after the dredging campaign (Van Dijken, 2020). Additionally, most of the siltation occurs in the winter months (Boorsma, 2019). In this period, the Doekegatkanaal entrance can have a siltation rate of 0.3 meters per month (Van Dijken, 2020).

Table 1: Maintenance Depth and Nautical Guaranteed Depth in meters below Normaal Amsterdams Peil (NAP) of the harbor basins and main channel. Information obtained from Boorsma (2019) and Groningen Seaports (2020).

Section	Maintenance Depth (m below NAP)	Nautical Guaranteed Depth (m below NAP)
Doekegatkanaal North	16.7	15.2
Doekegatkanaal Middle/South	16.2	15.2
Beatrixhaven	10.2 - 11.8	9.0
Julianahaven	14.0 – 17.0	13.0 – 16.5
Emmahaven	10.0	-
Wilhelminahaven	15.7 – 17.9	15.2 – 17.4

Subsequently, Antea Group has done a waterbed research in the harbor to analyze the content and environmental quality of the mud which has to be dredged (Boorsma, 2019). The bed in the harbor consists of silt, silt mixed with sand, and small to reasonably coarse sand with the addition of clay at the harbor entrance (Boorsma, 2019). They found that the dredged material conforms to the environmental standards and can be safely deposited within the estuary (Boorsma, 2019). The dredged material is dumped in the Oude Westereems (Van Dijken, 2020) at three specified locations. Approximately 40-45% is deposited near the harbor entrance, 50-55% about 4-6 kilometers westward of the entrance and 5% 9-10 kilometers westward in the Oude Westereems (Van Dijken, 2020). The choice of these locations and the timing of deposition is based on the fact that ideally, the dumped sediment will be taken up by the system as quickly as possible to prevent that sediment will remain in suspension and influence the ecology of the estuary (Koolstra et al., 2008). Even the dumping of uncontaminated dredge can lead to “anoxic conditions” (Kirby, 2013). The dumped dredged material will partly suspend in the water column but mostly fall to the bed relatively quickly (Koolstra et al., 2008). Part of this will remain as a new bed-layer at the dumping site, but most will be eroded due to strong currents within a few months after dumping and redeposit within the estuary (Koolstra et al., 2008).

5. PHYSICAL PROCESSES IN THE ESTUARY

Van Maren et al. (2014) explain that the transport of sediment "is determined by a range of processes, which operate on various time and spatial scales". In this section, the mechanisms which transport sediment throughout the estuary are explained and the natural processes at the basis of these mechanisms are qualitatively described.

Sediment transport mechanisms in an estuary

Grasmeijer & Pasmans (2013) explain that the sediment which is transported throughout the estuary comes from the bed at the entrance to the estuary which is brought into suspension through erosion by waves and tidal flows. The dominant natural processes shaping the transport of these sediment particles are the tides, wind, freshwater and salt water inflow and the complex interplay of the resulting hydrodynamics with the specific geography of the estuary and the sediment characteristics (Van Maren et al., 2011). As a result of these dynamics, both a landward and seaward directed transport of sediment occurs and interacts (Van Maren et al., 2014).

The transport of sediment directed toward the Ems river is formed by the combined effect of "tidal flow asymmetry, settling lag and scour lag effects, and the effects of estuarine circulation" (De Bruijn, 2018). First, tidal flow asymmetry is a difference in the duration and magnitude of the current velocity of ebb and flood which is caused by the interaction of the tidal flow with the morphology of the estuary and also the interaction between the different sources causing the tides (Grasmeijer & Pasmans, 2013; Van Maren et al., 2014). Second, settling lag is the effect that a higher current velocity is needed to erode a particle from the bed than keeping it in suspension (De Bruijn, 2018). Third, scour lag is the effect that there is a time delay between the current decreasing below a certain velocity to keep a particle in suspension and that particle dropping to the bed (De Bruijn, 2018). Lastly, estuarine circulation is the result of horizontal density gradients in both sediment concentration and salinity throughout the estuary (Van Maren et al., 2014; Baptist & Phillipart, 2015). The resulting interplay between these mechanisms is a gravitational circulation. This circulation causes a water flow directed toward the sea near the water surface and a water flow directed toward the Ems river near the bottom (Van Maren et al., 2016). Consequently, as the concentration of suspended sediment increases toward the bed, this leads to a transport of sediment toward the Ems river (Van Maren et al., 2016).

The sediment transport directed toward the Wadden Sea is a result of residual flow created by river flow and wind and "wave-induced resuspension combined with tidal mixing" (Van Maren et al., 2014). Water currents as a result of waves and wind erode sediment on the beds which cause a gradient of suspended sediment along the estuary (Van Maren et al., 2014). Additionally, the mixing of these suspended sediments due to tidal currents "leads to net down-estuary transport" (Van Maren et al., 2014).

Each of these processes act on specific time scales and differ in magnitude at different locations in the estuary. To understand and model these processes and the resulting sediment dynamics, qualitative data on the estuarine bed, sediment characteristics, tides, current flow, wind, and salinity in the estuary must be acquired.

Bed morphology and sediment characteristics

The bed morphology of an estuary is characterized by its sediment characteristics, water depth, presence of channels and dunes, and areas such as mud- and sandflats, also called "intertidal" areas (Dame, 2008). Van Maren et al. (2011) explain that the bed often has a gradient in density and shear strength with increasing depth. The upper layer is often thin and has a low density, which means that it can more easily erode under certain hydrodynamic conditions, whilst the bed becomes more dense and therefore harder to erode with increasing depth as particles will stick together and consolidate (Van Maren et al., 2011).

The depth characteristics of the estuary are illustrated in Figure 4 below. This map is a combination of the depth of the bed, water height, and times of dry-fall (Ysebaert et al., 2016). As can be seen in the figure, the main channel winding through the estuary and passing the Eemshaven, is classified as a combination of deep and shallow sub-intertidal areas. In deep sub-intertidal sections, the bed is deeper than 5 meters below the average low water springtide and in the shallow sub-intertidal sections there is an additional characteristic that the bed falls dry for at most 4% of the time due to the tidal movements (Ysebaert et al., 2016). The areas shrugging the coast and the main channel are mostly low and middle intertidal areas which are characterized respectively by 4-25% dry-fall of the bed accompanied by average lower water springtide height for the low- and 25-75% dry-fall of the bed for the middle littoral areas (Ysebaert et al., 2016). In the Dollard area, there are mostly high and middle intertidal areas (Grasmeijer & Pasmans, 2013).

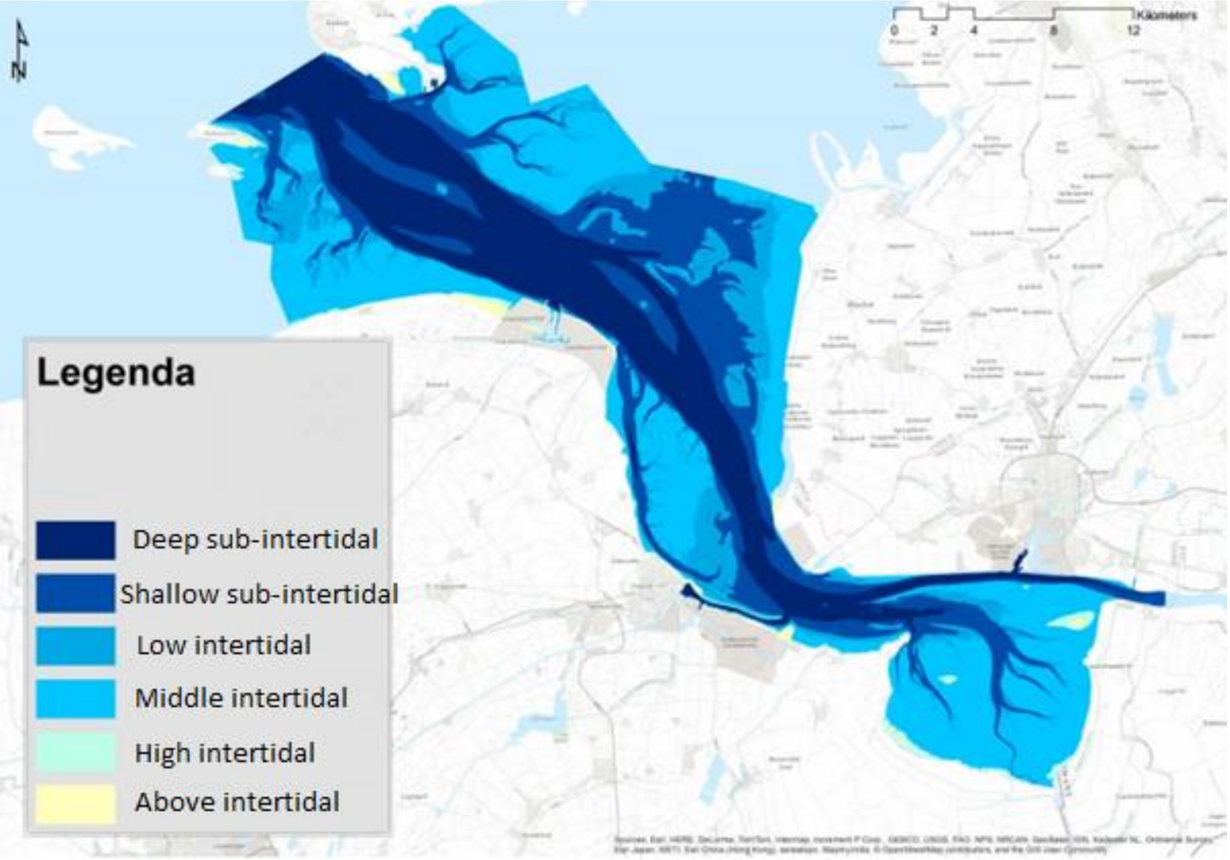


Figure 4: Depth characteristics throughout the estuary. Above intertidal areas fall dry over 85% and is above the average high water slack tide, high intertidal areas, middle intertidal, and low intertidal areas fall dry between 75-85%, 25-75%, and 4-25% respectively, Shallow sub-intertidal areas are 5 meters below average low water spring tide and fall dry less than 4% and deep sub-intertidal areas are deeper than 5 meters below average low water spring tide Ysebaert et al. (2016). Taken and adapted from Ysebaert et al. (2016).

Subsequently, the characteristics of the sediment in the estuary are important for understanding the processes of erosion, transport and deposition of sediment throughout the estuary (PIANC, 2008). The source of sediment at the Eemshaven is mostly from the North Sea and Wadden Sea and only during "high discharge conditions" (Van Maren et al., 2015) does the Ems river contribute to the sediment concentration in the estuary (Van Maren et al., 2015). Van Maren et al. (2015) argue that the Ems river on average over the year acts as a sink rather than source of sediment.

In general, sediment is classified by its “organic content, grain size, and cohesiveness” (PIANC, 2008). The grain size ranges from clay (<4 µm), silt (4-64 µm), very fine to very coarse sand (64 – 2000 µm), and pebbles, cobbles and boulders (>2000µm) (Costa, 2016). Sharp et al. (2010) explain that large sediment, like sand, are non-cohesive but smaller particles, like clay and silt, flocculate quite easily. Organic particles such as plant or animal fragments can bind to sediment particles and enhance the flocculation process (Sharp et al., 2010; Van Duren et al., 2011). Flocculation is basically the sticking together of smaller sediment particles into a larger particle with a larger settling rate and decreasing rate of erosion (Van Maren et al., 2014; Van Duren et al., 2011). Larger particles can only be transported by rolling and sliding across the bed whilst fine, cohesive sediment particles such as clay and silt are more easily picked up from the bed by the water flow and transported in suspension (Sharp et al., 2010). The distribution of the different types of sediment throughout the estuary is illustrated in Figure 5. In general, Grasmeijer & Pasmans (2013) found that the sediment in the deep channels are mostly sand with median grain size between 180-600 µm. The shallow sections of the estuary consist of silt and sand with median grain diameter between 60-240 µm (Grasmeijer & Pasmans, 2013).

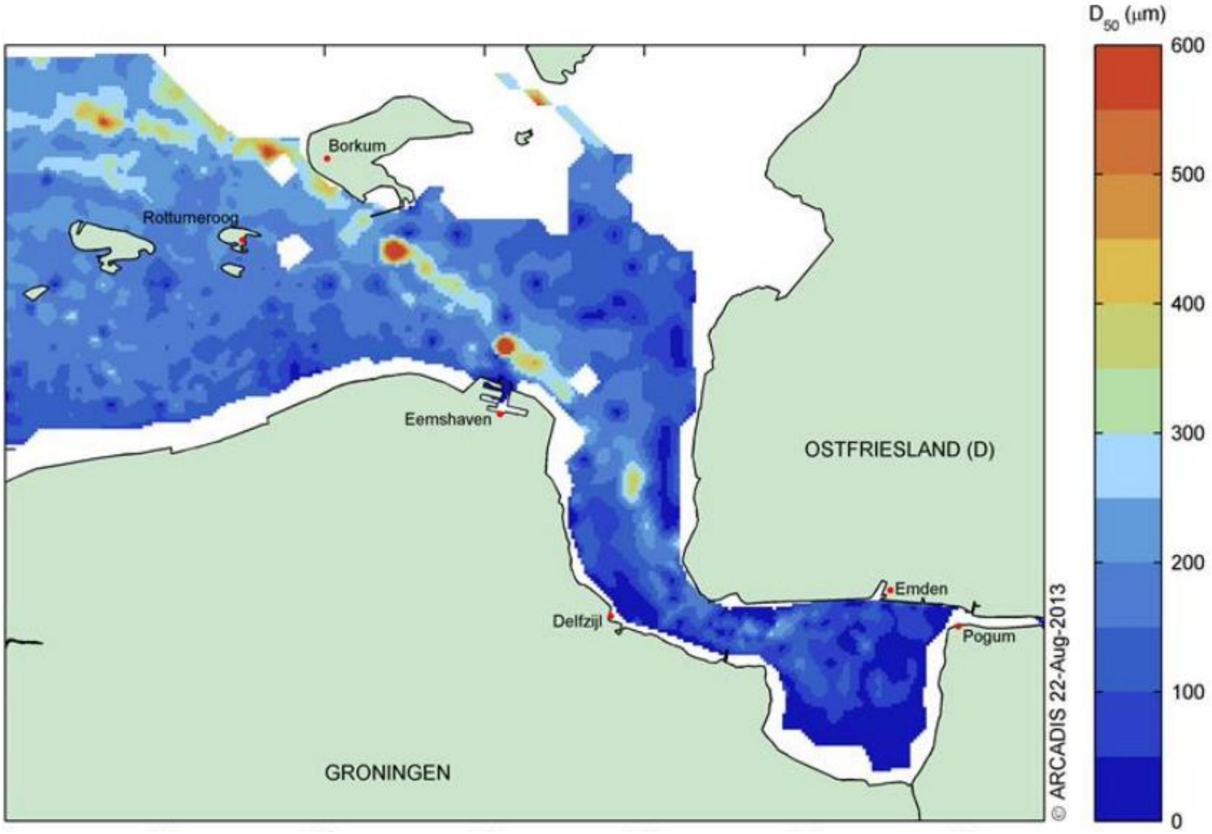


Figure 5: Median grain size diameter of sediment throughout the Ems estuary. Taken from Grasmeijer & Pasmans (2013).

Additionally, most of the sediment transported in an estuary are fine, suspended sediment particles (Chernetsky, 2012; Sharp et al., 2010) which is a mixture of biological and non-biological particles such as clay and silt (Grasmeijer & Pasmans, 2013). The suspended sediment concentration, or SSC, varies within the tidal cycle (Grasmeijer & Pasmans, 2013) and also has a seasonal variation where it is higher during the winter months than the summer months (Decrop, 2013). Furthermore, it has a large spatial variation throughout the estuary, as shown in Figure 6. This is due to tidal asymmetries, both in terms of velocity magnitude and duration, gravitational circulation (Van Maren et al., 2016) and wind flows (Grasmeijer & Pasmans, 2013). In the short term, the dumping of dredge influences the SSC as well (Grasmeijer & Pasmans, 2013). An interesting phenomenon resulting from these processes is the Estuarine Turbidity Maximum (ETM). This is an area, the location of which varies slightly in time, where the suspended sediment concentration is highest as here the sediment is trapped. This trapping is caused by the reversal of a landward directed, near-bed current due to river inflow (Baptist & Phillipart, 2015). The ETM in the Ems estuary is situated in the Dollard basin near Emden (Baptist & Phillipart, 2015).

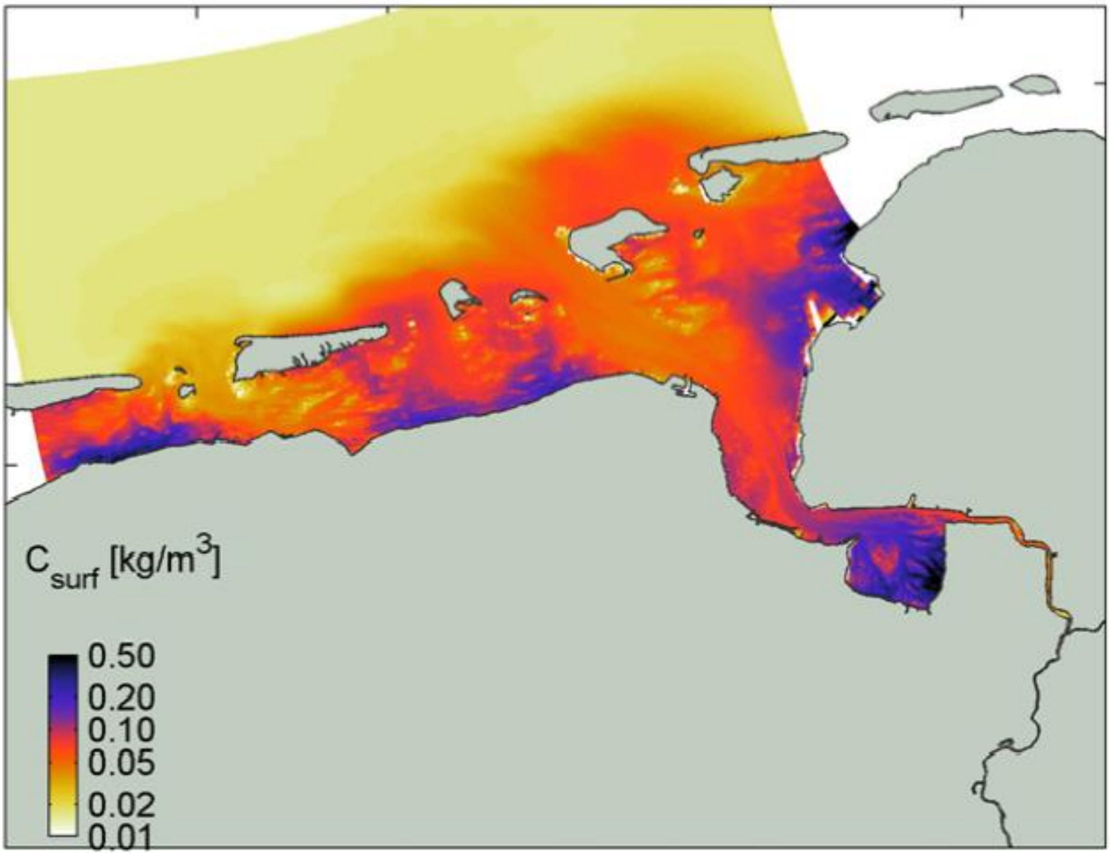


Figure 6: The modelled yearly averaged suspended sediment concentration (SSC) at the water surface in kg/ m^3. Taken from Van Maren et al. (2016).

Tides and wind

Both the incoming and outgoing tidal energy and the wind affect the sediment and its transport in an estuary (Van Maren et al., 2014; Grasmeijer & Pasmans, 2013). The tidal energy progressing through the estuary is quite complex. Tidal waves are produced by the interplay between “gravitational effects of the moon and sun on the ocean” (Parker, 2016) and originate in the deep ocean (Parker, 2016)**.** The force they have on the water is periodic and each individual force contributes to this tidal energy in terms of amplitude and phase (Parker, 2016). The main constituent is the so-called M2 which represents the Earth-Moon interaction and has two high waters per day (Parker, 2016). Additionally, another important constituent is called M4 (Parker, 2016). This is the first overtide which is created by the distortion of the tidal energy due to the transition from deep to shallow waters (Parker, 2016). The interaction between the M2 and M4 component leads to asymmetries (Grasmeijer & Pasmans, 2013). These asymmetries can be a difference in the duration of high and low water and a difference in maximum flood and ebb current velocity (Van Maren et al., 2014; Grasmeijer & Pasmans, 2013). Chernetsky et al. (2010) argue that tidal asymmetries result in temporal settling lag which in turn leads to sediment-size-dependent transport of suspended sediment in a specific direction depending on the asymmetry. This settling lag is caused by the fact that the M2 and M4 interaction can create a difference in slack time between ebb and flood (Grasmeijer & Pasmans, 2013). Grasmeijer & Pasmans (2013) argue that if the slack time before ebb is longer than the slack time before flood, silt is imported in that region due to the time it has to settle. Therefore, obtaining the specific values of the tides in the Ems estuary is important.

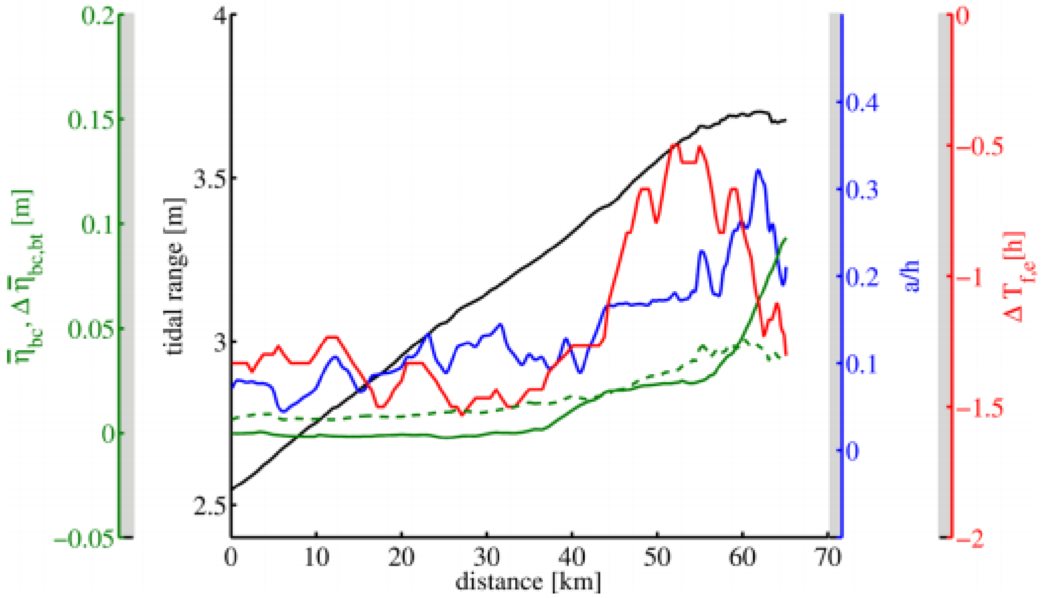


Figure 7: Illustration of the tidal characteristics throughout the Ems estuary where the x-axis refers to the distance with respect to Borkum. Illustrated are the tidal range (black line), tidal range divided by water depth (blue line), tidally averaged water level (solid green line), and the difference in duration between flood and ebb (red line). The Eemshaven is approximately at the 20-25 km mark. Taken from Pein et al. (2014).

In Figure 7 above, the tidal range (black line), tidal range divided by water depth (blue line), the tidally averaged water level (solid green line), and the difference in duration between flood and ebb (red line) are illustrated. The x-axis displays the distance from the North Sea where 0 km is the location at Borkum and Rottumeroog and 65 km the inlet of the Ems river into the Dollard basin (Pein et al., 2014). The Eemshaven is at approximately 20-25 km. First, it can be seen that the tidal range increases almost linearly from 2.6 m at 0 km to 3.8 m at 65 km where it decreases slightly between 55 and 65 km (Pein et al., 2014). This trend is due to the shape of the estuary where the coast converges at the entrance of the estuary and eventually runs parallel as it proceeds to the Ems river (Pein et al., 2014). Second, the difference in time duration between flood and ebb is important. The positive values in Figure 7 signify how much longer ebb lasts than flood. As can be seen, between 0 and 40 km from the estuary inlet, the ebb tide lasts more than one hour longer than the flood tide. This reduces to around half an hour between 45-55 km, and after that increases beyond one hour again. Furthermore, the phase difference between the M2 and M4 constituents at the Eemshaven is such that there is an import of fine sediment, or silt (Grasmeijer & Pasmans, 2013).

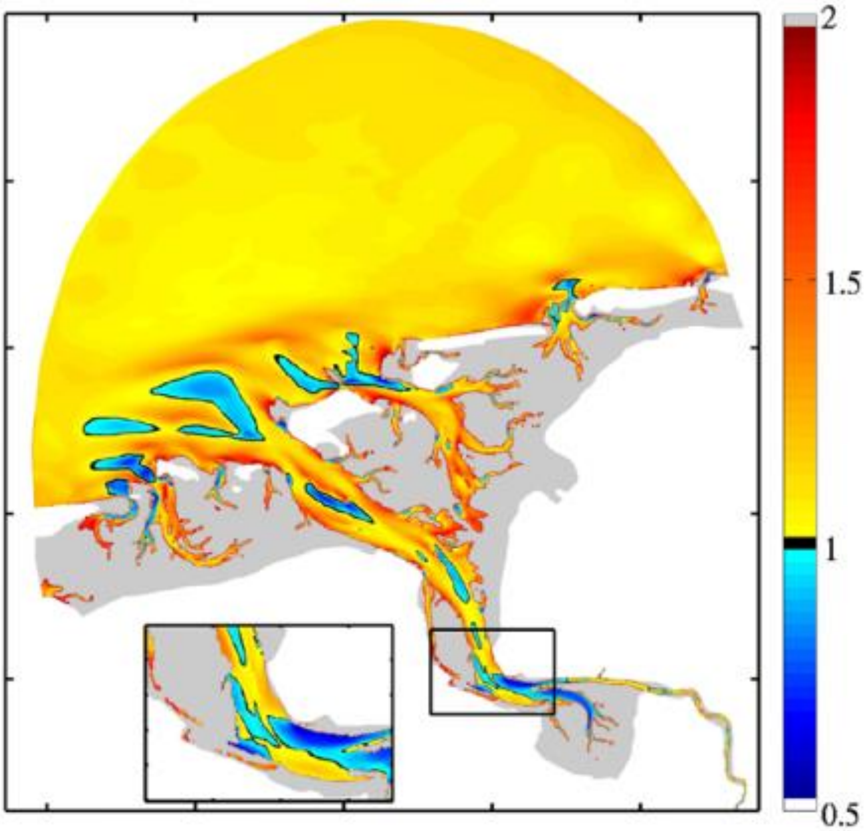


Figure 8: The ratio of maximum flood over maximum ebb depth-averaged velocity. Values above 1 (red) indicate a flood dominant region whilst values lower than 1 (blue) indicate an ebb dominant region. Taken from Pein et al. (2014).

Additionally, Pein et al. (2014) argue that asymmetries in the tidal flow currents and their spatial variation throughout the estuary "control the sediment dynamics". Figure 8 above illustrates the ratio of maximum flood and maximum ebb current velocities throughout the estuary. Values above 1 (red) indicate a flood dominant region whilst values lower than 1 (blue) indicate an ebb dominant region (Pein et al., 2014). It can be seen that there is a flood dominant region in the main channel which runs between the Dollard region and the outer estuary (Pein et al., 2014). Here the "tidal wave propagates faster during flood than during ebb because during [ebb] the local depth is shallower" (Pein et al., 2014) enhancing the friction between river bed and the water flow. Contrarily, the Dollard basin consists of large tidal flats and separates the water flow into water flowing into the basin and water going up the Ems river (Pein et al., 2014). Its morphology delays "the propagation of the flood while enhancing the ebb-current" (Pein et al., 2014) creating an ebb dominant hydrodynamic region.

Lastly, wind and wind-induced waves and currents influence the water movements in the estuary as well (Grasmeijer & Pasmans, 2013). For example, wind and waves can "stir up sediment from tidal flats" (Van Maren et al., 2014) when they are exposed. Thus, as the estuary is quite shallow, "locally generated waves play a major role in the sediment dynamics" (Spiteri et al., 2011). Detailed and up-to date wind data can be found on the website of Rijkswaterstaat. Additionally, Sharp et al. (2010) illustrate the importance of episodic events such as storms when saying that "in some cases more sediment is transported in one storm event than in all the rest of the year".

Freshwater and salinity

It is important to analyze the salinity throughout the estuary as salinity gradients drive an estuarine circulation which is an important mechanism for sediment transport (Van Maren et al., 2014). In the estuary, salt water from the Wadden Sea brought in by the tides is mixed with the freshwater inflow coming primarily from the Ems river (Baptist & Philippart, 2015). This freshwater inflow varies throughout the year (Grasmeijer & Pasmans, 2013). During summer months between 10-40 m^3/s and during winter months between of 80-110 m^3/s flows into the Dollard basin with sometimes a maximum of 600 m^3/s during particularly wet winter months (Talke et al., 2009). This causes salinity gradients throughout the estuary where at Eemshaven the salinity is almost 3 times as high than at Emden (Litjens et al., 2013). The vertical and horizontal salinity gradients vary in time and throughout the estuary. On the one hand, there is only a very slight vertical salinity gradient throughout the estuary mostly toward the Dollard bay and the Ems river during flood, as can be seen in Figure 9c and d. On the other hand, during ebb, there is a significant vertical salinity gradient from 60 km onward and between 40-45 km. This reflects the situation where “relatively fresh water is advected over saltier water” (Pein et al., 2014). However, from Figure 9c and d it becomes clear that in the outer estuary, between approximately 0 and 30 km where the Eemshaven is settled, the vertical difference in salinity is negligible which means that it is vertically well-mixed (Pein et al., 2014; Baptist & Philippart, 2015).

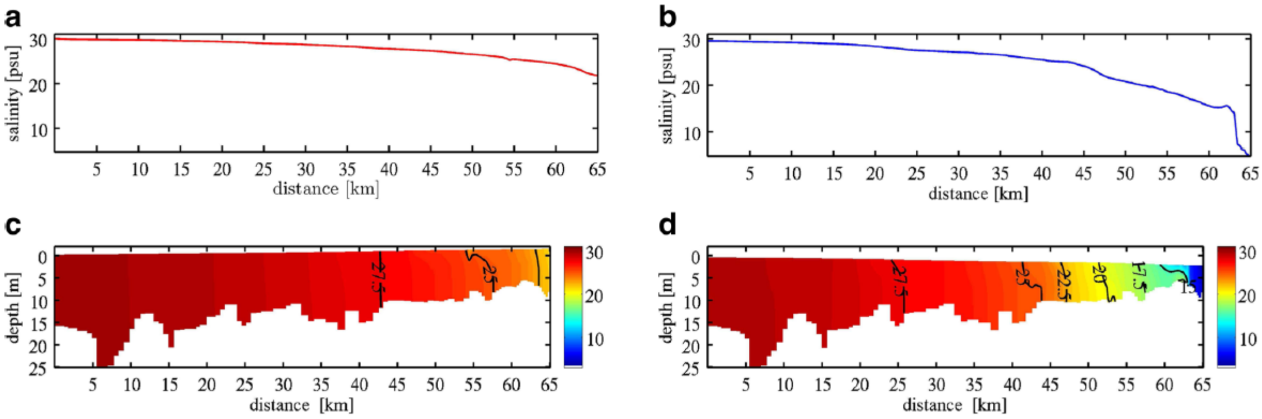


*Figure 9: vertically averaged salinity in psu (practical salinity units) along the main channel during flood **a)** and ebb **b)**. Figures **c)** and **d)** display the vertical salinity along the main channel during flood and ebb respectively**.** All figures are made on the basis of measurements on the 6th of June 2012 between 14:00 and 20:50. Taken from Pein et al. (2014).*

Additionally, as the water is vertically well-mixed, the horizontal variation of salinity throughout the estuary is of more importance (Grasmeijer & Pasmans, 2013). The depth-averaged salinity throughout the estuary at high and low water at Eemshaven are illustrated in Figure 10 and Figure 11 respectively below.

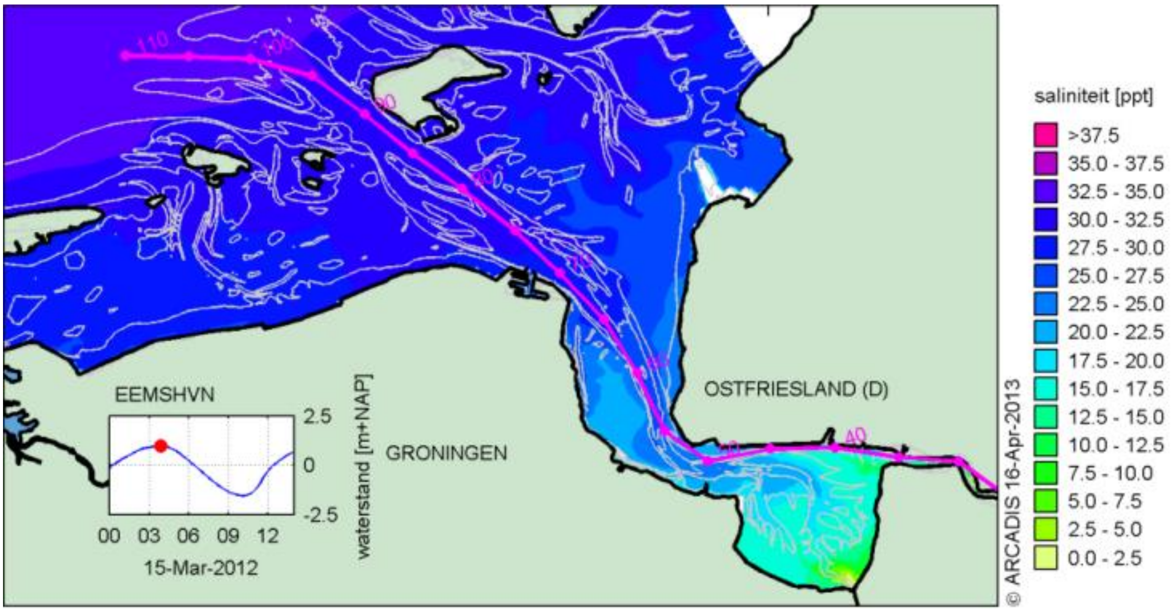


Figure 10: Depth averaged salinity in ppt (parts per trillion) during high water at Eemshaven for an average tide in the Ems estuary. Taken from Grasmeijer & Pasmans (2013).

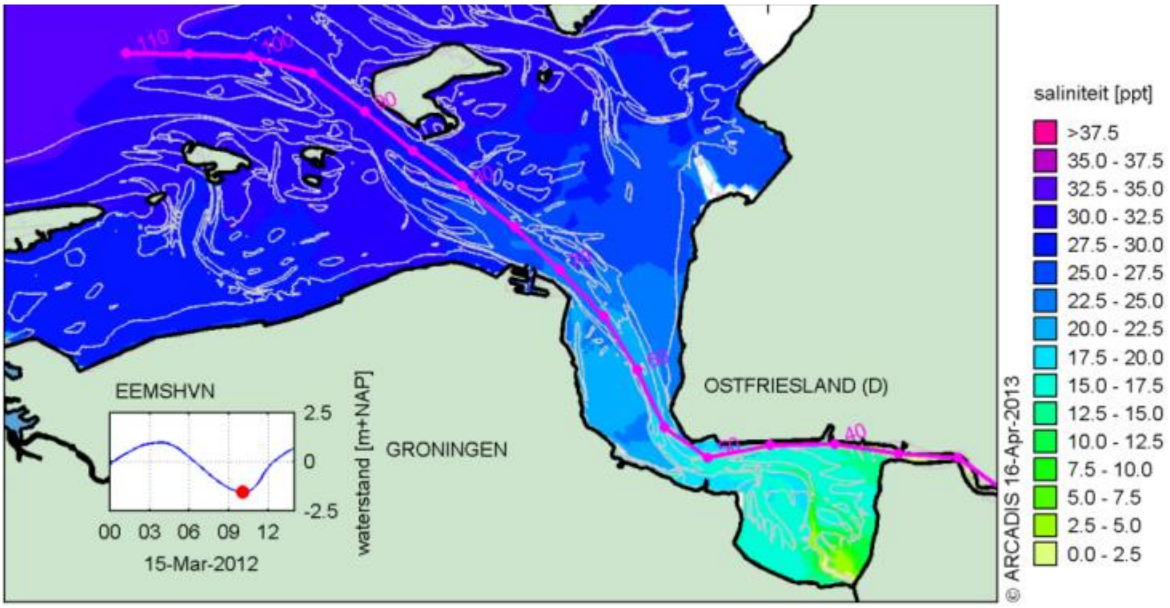


Figure 11: Depth averaged salinity in ppt (parts per trillion) during low water at Eemshaven for an average tide in the Ems estuary. Taken from Grasmeijer & Pasmans (2013).

During ebb, the freshwater inflow from the Ems river reaches almost up to the Eemshaven as can be seen in figure 11. However, it appears that the salinity at the Eemshaven is not affected significantly by the freshwater inflow, during neither ebb nor flood, as the salinity at the Eemshaven is similar to the salinity in the North Sea. Subsequently, the salt water coming in from the North Sea during flood is mixed throughout the estuary with freshwater. The salinity reaches its lowest values in the Dollard basin as can be seen in the figures. It is worth noting that Grasmeijer & Pasmans (2013) use the units psu and ppt interchangeably. Therefore, this study assumes that these units are similar.

6. SEDIMENT EXCHANGE BETWEEN THE ESTUARY AND THE EEMSHAVEN

The processes described in the previous sections occur in the estuary as a whole. These processes determine the sediment- and hydrodynamics outside of and toward the Eemshaven. However, within the estuarine system, the Eemshaven is a “near-perfect sediment trap” (Van Maren et al., 2014) where sediment brought in from the estuary can settle due to its tranquil environment (PIANC, 2008). Therefore, a good understanding of the exchange of sediment between the estuary and the harbor is important (PIANC, 2008). In this section, the exchange mechanisms, their interaction and their relevance to the Eemshaven harbor are explained and qualitatively analyzed.

Siltation rate

Winterwerp (2005), PIANC (2008), and Kirby (2011) describe the siltation rate F_s of a harbor in contact with a water system mathematically as:

$$F_s = p \times c_a \times Q \qquad [1]$$

where p is the trapping efficiency of the harbor, c_a the ambient sediment concentration outside the harbor and Q the rate of water exchange between the harbor and the surrounding water. Subsequently, the rate of water exchange Q is further subdivided by Winterwerp (2005), Barneveld & Hugtenburg (2008), PIANC (2008), and Langendoen (1992) into three main mechanisms:

- Tidal filling
- Density driven currents
- Horizontal entrainment (turbulent mixing layer)

In addition to these three mechanisms, ship movement can also influence the water exchange (PIANC, 2008). However, this will not be included in this research as it is difficult to quantify and reduce its effect (PIANC, 2008).

Tidal filling

First, there is an exchange of sediment and water due to the tides continuously filling and emptying the harbor (Winterwerp 2005; PIANC, 2008; Langendoen, 1992). This mechanism both directly brings sediment into the harbor but mostly influences the exchange rate of the other two mechanisms (Decrop, 2013). The exchange flow Q_t is given by equation 2 and depends on the tidal amplitude a, the area of the harbor basin S and the tidal period T (PIANC, 2008):

$$Q_t = 2a \times S/T \qquad [2]$$

The siltation rate depends on how much of the sediment brought in by the rising tide settles and consolidates on the harbor bed, which mostly occurs during slack tide (Van Maren et al., 2014), and is not removed by the ebb current flowing out of the harbor. This removal rate depends on the water flow in the harbor and ship movement which can stir up the sediment (PIANC, 2008).

Density driven currents

Second, water and sediment exchange between a river and a harbor is also influenced by density-driven currents (Winterwerp 2005; PIANC, 2008; Langendoen, 1992). These currents are caused by density gradients between the harbor and the surrounding water in salinity, temperature, or sediment concentration or a combination of these (Winterwerp, 2005; Langendoen, 1992). The exchange rate in case of a salinity gradient is given by equation 3 (PIANC, 2008):

$$Q_d = f_d A \sqrt{\frac{\Delta\rho_m}{2\rho} g h_0} - f_{t,d} Q_t \qquad [3]$$

Thus, it depends on the water depth in the harbor h_0, the gravitational constant g, the cross section of the entrance of the harbor A, the density difference between the harbor and the estuary $\Delta\rho_m$, the density of salt ρ, an exchange coefficient f_d and its interaction with the tidal filling mechanism $f_{t,d}Q_t$ (PIANC, 2008). The terms $f_{t,d}$ and f_d reflect the phase difference between the tides and the temporal variation in salinity (PIANC, 2008). The exchange coefficient f_d varies from 0.125 for large harbors to 0.05 for small harbors (PIANC, 2008).

The exchange mechanism is illustrated in Figure 12 for a salinity gradient and works as follows. For example, during rising tide, the river salinity is usually higher than the salinity in the harbor (De Bruijn, 2018). Decrop (2013) explains that as salt water has a higher density than freshwater, $\rho_s > \rho_f$, this leads to a horizontal density gradient between a harbor and a river. This is then compensated by a gradient in water level in the vertical direction which, due to the resulting vertical hydrostatic force (Decrop, 2013), generates "gravitational circulation" (Winterwerp, 2005). This results in a near-bottom inflow of river water into the harbor and a surface current in the opposite direction (Decrop, 2013; De Bruijn, 2018). As the water near the bed contains most of the sediment (Van Maren et al., 2016), this leads to an influx of sediment into the harbor.

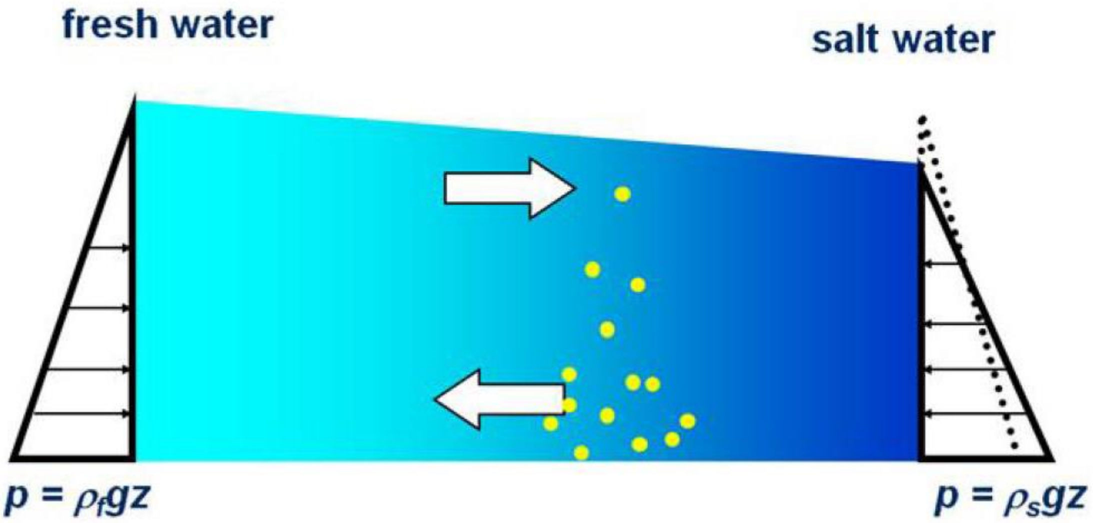


Figure 12: Illustration of the flow of water due to density driven currents. Salt water has a higher density than freshwater which leads to a difference in hydrostatic pressure forcing near-bed water to flow to the freshwater region and near-surface water to the salt water region. Taken from De Bruijn (2018).

Horizontal Entrainment (turbulent mixing layer)

Lastly, a prominent exchange of water and sediment is caused by the horizontal entrainment or turbulent mixing layer effect (Langendoen, 1992). The mechanism is illustrated in Figure 13 below.

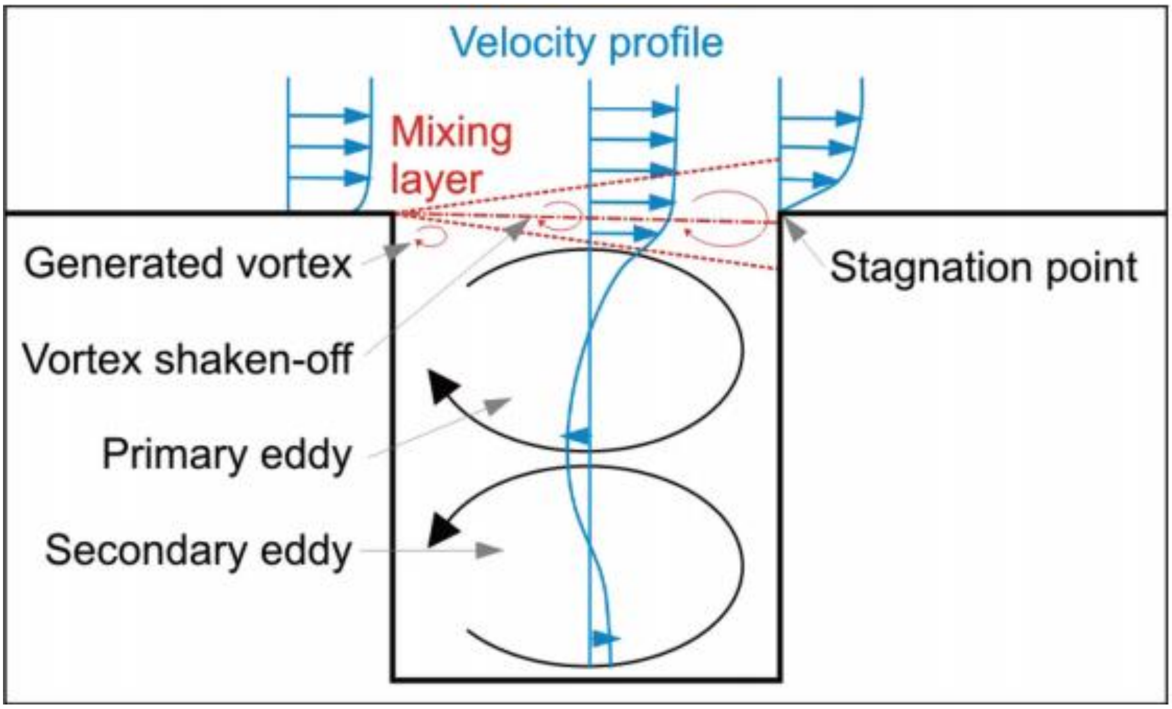


Figure 13: illustration of horizontal entrainment process due to velocity differences between the river and a harbor. Taken from Barneveld & Hugtenburg (2008).

The exchange rate of this mechanism is approximately given by (PIANC, 2008):

$$Q_e = A \times f_e \times u_r \qquad [4]$$

Here, u_r is the water flow velocity in the river, A the cross-sectional area of the entrance of the harbor and f_e the exchange coefficient (Winterwerp, 2005; PIANC, 2008). The exchange coefficient depends on the shape and geometry of the harbor and its entrance, specifically the "angle of the downstream corner of the harbor mouth" (Winterwerp, 2005) and the angle of the harbor with respect to the river (Kuijper et al., 2005). Kuijper et al. (2005) argue that the coefficient increases for decreasing angle of the harbor with respect to the river and ranges between 0.005 and 0.05.

The transport of matter into the harbor and throughout the harbor are driven by the mixing layer and eddies at the entrance and within the harbor (Langendoen, 1992). At the upstream corner of a harbor, the water flow separates, creating a significant difference in flow velocities between the river and the harbor which in turn creates "wave-like disturbances" (Langendoen, 1992). These disturbances, or vortices, increase toward the stagnation point at the downstream side of the harbor entrance and form the mixing layer (Langendoen, 1992). These vortices and disturbances capture the water coming from the river and the harbor and when this water flows against the downstream side, part of it will flow into the river and part into the harbor (Langendoen, 1992). Therefore, if water from the river contains sediment, it will be captured and mixed and can flow into the harbor as well in this process (Langendoen, 1992). Subsequently, the sediment coming out from the mixing layer enters the harbor and is distributed around the harbor via eddies. Eddies are created due to "entrainment of harbour water into the mixing layer and the supply of water from the mixing layer into the harbour near the stagnation point" (Langendoen, 1992). The number of eddies and their shape depend on the bathymetry (Kuijper et al., 2005) and geometry of the harbor, specifically the ratio of length to width and the angle of the harbor with respect to the river (Langendoen, 1992). These eddies are important for the transfer of sediment into the harbor as sediment will move toward the center of the eddy and deposit as the current velocity is small there (Langendoen, 1992).

Interaction between mechanisms

In reality, the exchange of sediment and water are the result of a complex interaction between these three mechanisms which vary in space and time (Langendoen, 1992). For example, on the one hand, the eddies in the harbor created by the horizontal entrainment effect can be "suppressed or hindered by the density-driven exchange flow" (Langendoen, 1992). On the other hand, El Hamdi (2011) argues that this interaction can also lead to more mixing of water which reduces the magnitude of the density-currents.

Additionally, the interaction between tidal filling and horizontal entrainment results in higher sedimentation in a harbor (Langendoen, 1992). This is due to the fact that during rising tide, the eddies narrow the water flow into the harbor which increases the velocity and thereby increases the sediment transport into the harbor where it can settle (Langendoen, 1992). Additionally, during ebb, the harbor is drained which decreases the strength of the eddies thereby lowering the velocities which can thereby not resuspend the deposited sediment (Langendoen, 1992). Furthermore, the mixing layer is pulled into the river during ebb which reduces the exchange rate as well (PIANC, 2008). This interaction, as illustrated in Figure 14, therefore increases the sedimentation in the harbor.

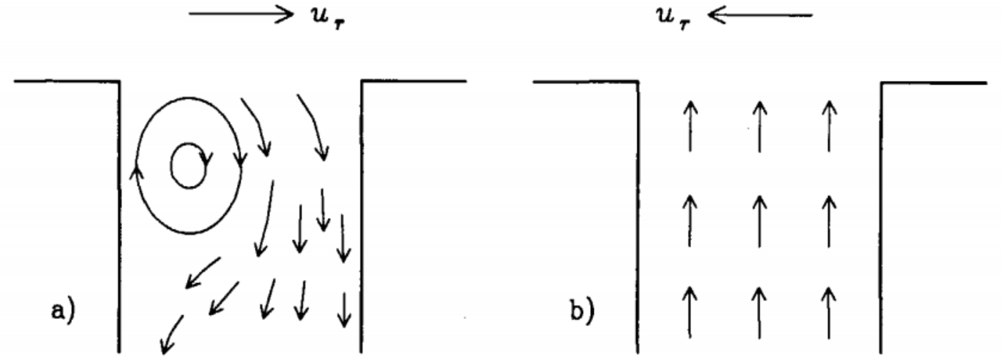
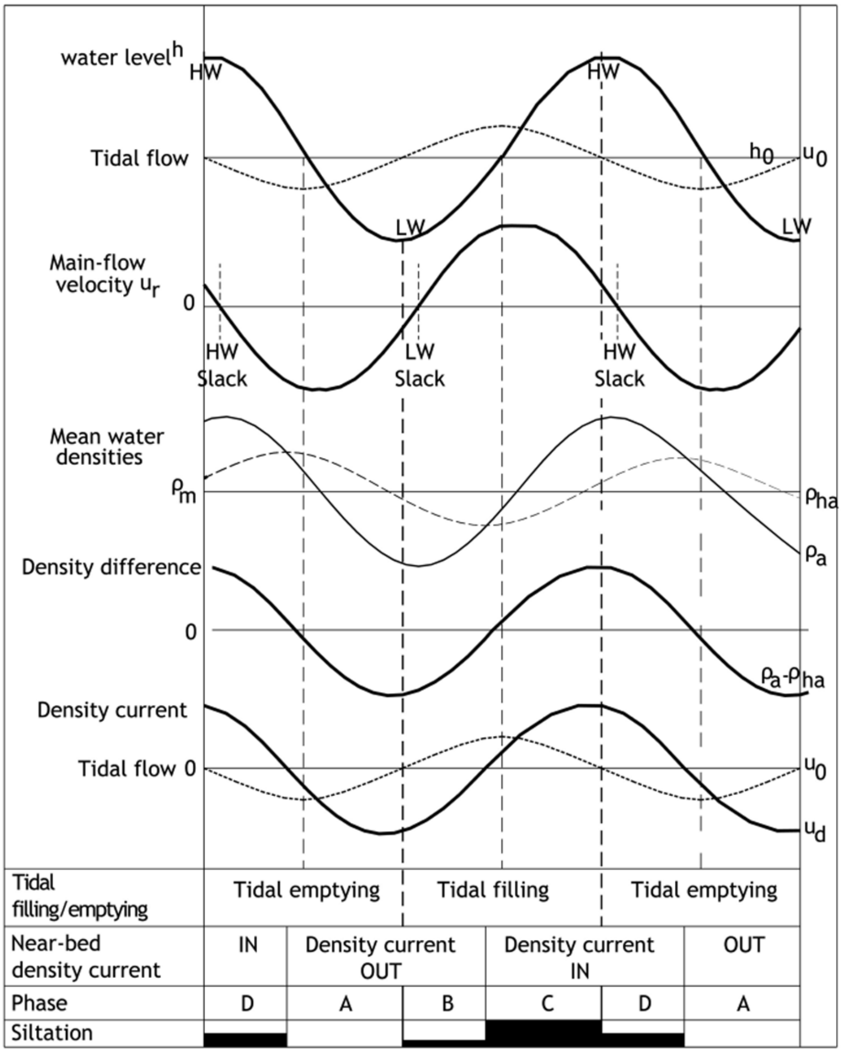


Figure 14: The water flow in a harbor with ***a)*** *the flow during flood and* ***b)*** *during ebb. Taken from Langendoen (1992).*

Lastly, there is a complex interaction between tidal filling and density driven currents which varies over the tidal cycle (PIANC, 2008). This is shown in Figure 15 below. Positive values in the graph signify a flow directed into the harbor and negative values into the estuary (PIANC, 2008).



Tidal filling/emptying	Tidal emptying		Tidal filling		Tidal emptying	
Near-bed density current	IN	Density current OUT		Density current IN		OUT
Phase	D	A	B	C	D	A
Siltation	■		■	■	■	

Figure 15: Illustration of the parameters determining the interaction between density driven currents, horizontal entrainment and tidal filling throughout a tidal cycle. Important parameters are the water level, tidal flow, main flow velocity, density difference, and density current. Taken from PIANC (2008).

Figure 15 illustrates that there are four phases in a tidal cycle where the interaction between the mechanisms lead to a certain siltation rate in the harbor. Siltation of the harbor occurs in increasing order in phases B, D and C while no siltation occurs during phase A. In phase B, tidal filling occurs but as the density of the water is higher in the harbor than in the river, the density current is directed out of the harbor which decreases the siltation rate (PIANC, 2008). In phase D, the density current is directed into the harbor but the tides are emptying the harbor. This is a destructive interference (PIANC, 2008). In phase C, there is a combination of tidal filling and a density current directed into the harbor in addition to a significant main water flow velocity in the estuary at high water (PIANC, 2008). Therefore, in this phase the siltation is highest as the mechanisms interfere constructively.

Identify exchange mechanisms at Eemshaven

In order to identify which of these mechanisms are prominent at the Eemshaven and the exact interaction of these mechanisms, qualitative knowledge of the natural factors are obtained.

Grasmeijer & Pasmans (2013) calculated and modelled the current velocities and direction at both maximum ebb and flood around Eemshaven as illustrated in Figure 16 and Figure 17 respectively. The current velocity approaches 0 m/s within the harbor whilst it can reach values between 0-1 m/s during maximum ebb and 0.6-1.2 m/s during maximum flood directed perpendicular to the harbor entrance depending on the distance from the harbor entrance (Grasmeijer & Pasmans, 2013). Therefore, there seems to be a significant difference in current velocity between the harbor and the estuary during these conditions.

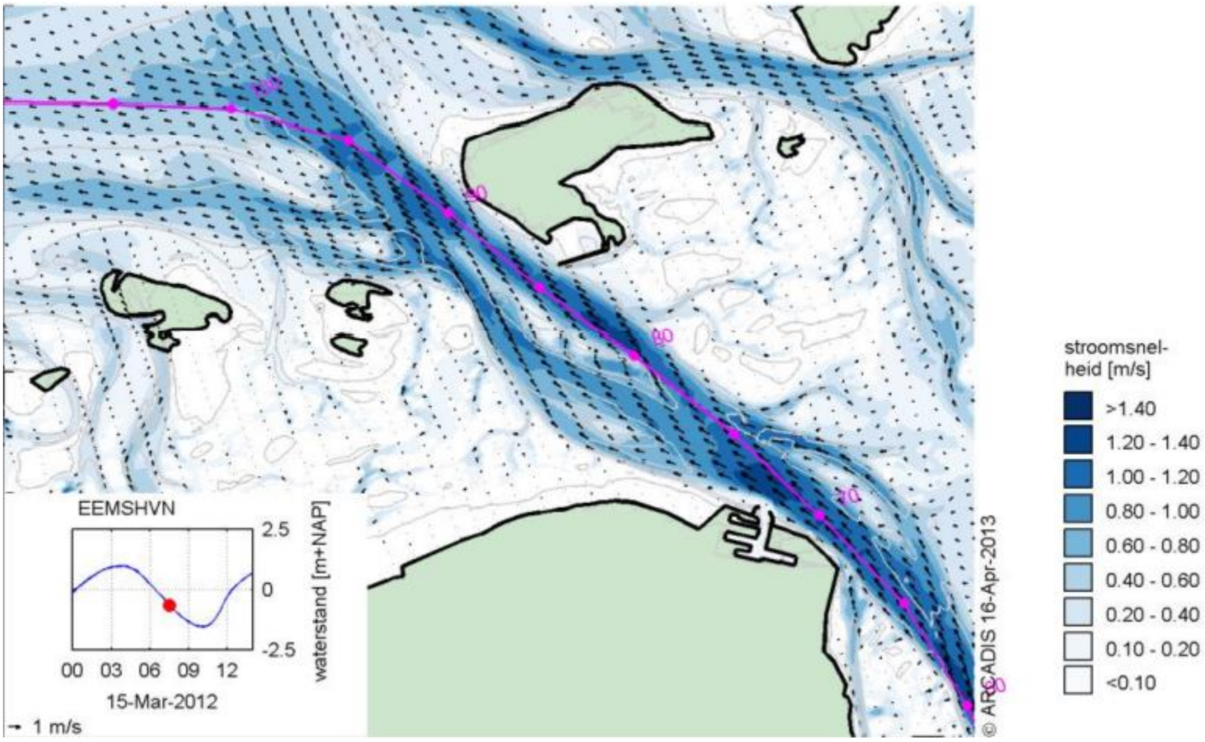


Figure 16: Depth averaged current flows in m/s during maximum ebb. Taken and adapted from Grasmeijer & Pasmans (2013).

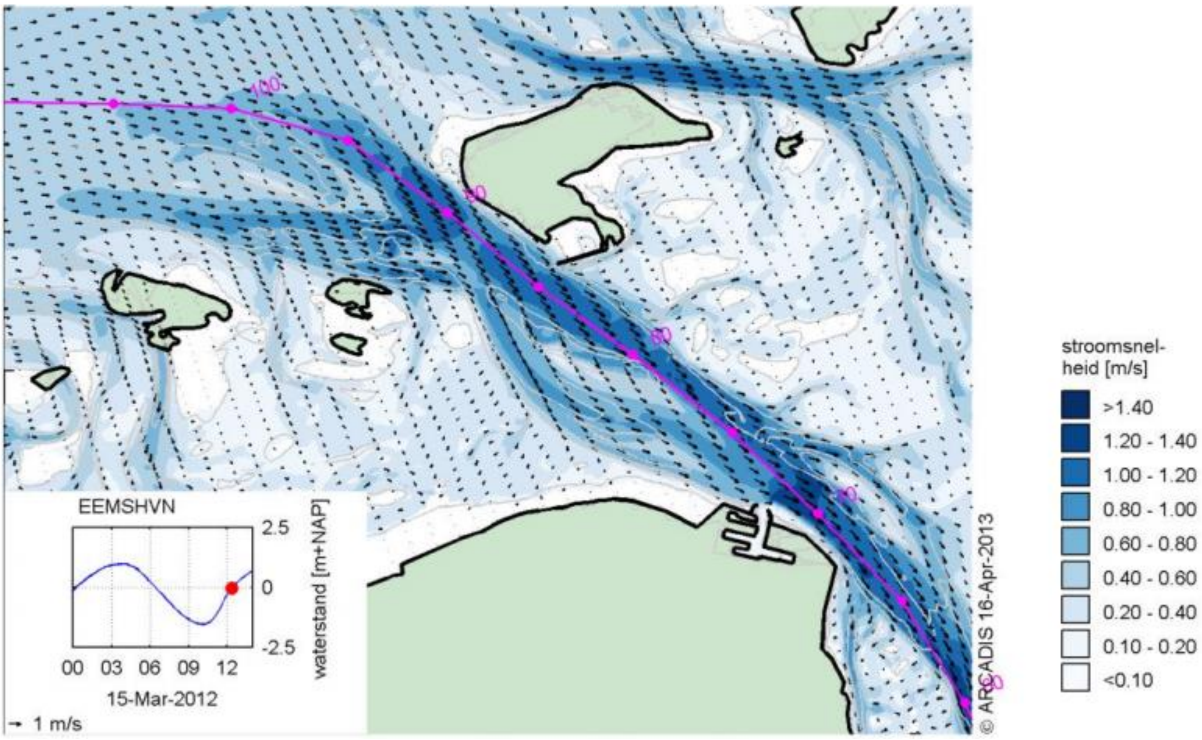


Figure 17: Depth averaged current flows in m/s during maximum flood. Taken and adapted from Grasmeijer & Pasmans (2013).

Additionally, the tidal range across several tidal cycles accompanied by the corresponding water flow velocities perpendicular to the harbor entrance within the main channel outside the Eemshaven harbor are illustrated in Figure 18 below. As can be seen in the figure, the tidal range varies approximately between 2.5 and 3 meters approximately over these tidal cycles. Additionally, the current velocity varies between 0 m/s during slack tide and between 1 and 1.5 m/s during maximum ebb and flood (Grasmeijer & Pasmans, 2013).

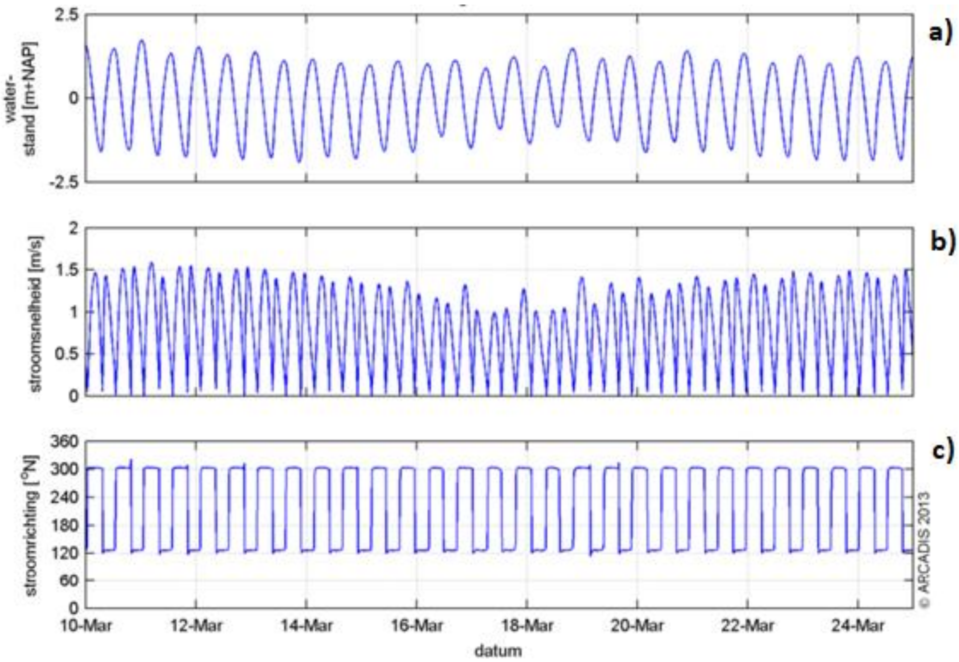


Figure 18: Calculated water height in meter relative to NAP ***a)****, current flow velocity in m/s* ***b)****, and direction of the current flow in degrees (°) with respect to North* ***c)****. Here, 300°N means ebb flow, and 120°N means flood flow perpendicular to the harbor entrance. Taken from Grasmeijer & Pasmans (2013).*

Lastly, the prominence of density driven currents due to salinity, temperature and sediment concentration gradients is investigated. First, Figure 9 is compared to the measured salinity in the Eemshaven as given in personal communications with Groningen Seaport (Van Dijken, 2020). The latest salinity measurements from 2010 in the month of June shows that the salinity within the harbor is 29.1 psu (Van Dijken, 2020) which is quite comparable to the salinity in the estuary as given in Figure 9, which is around 30 psu. Second, the nearest station measuring the suspended sediment concentration is located a few kilometers from the Eemshaven harbor. The observed sediment concentration near the surface and near the bed is given in Figure 19a and b respectively. Unfortunately, the suspended sediment concentration within the Eemshaven is not known.

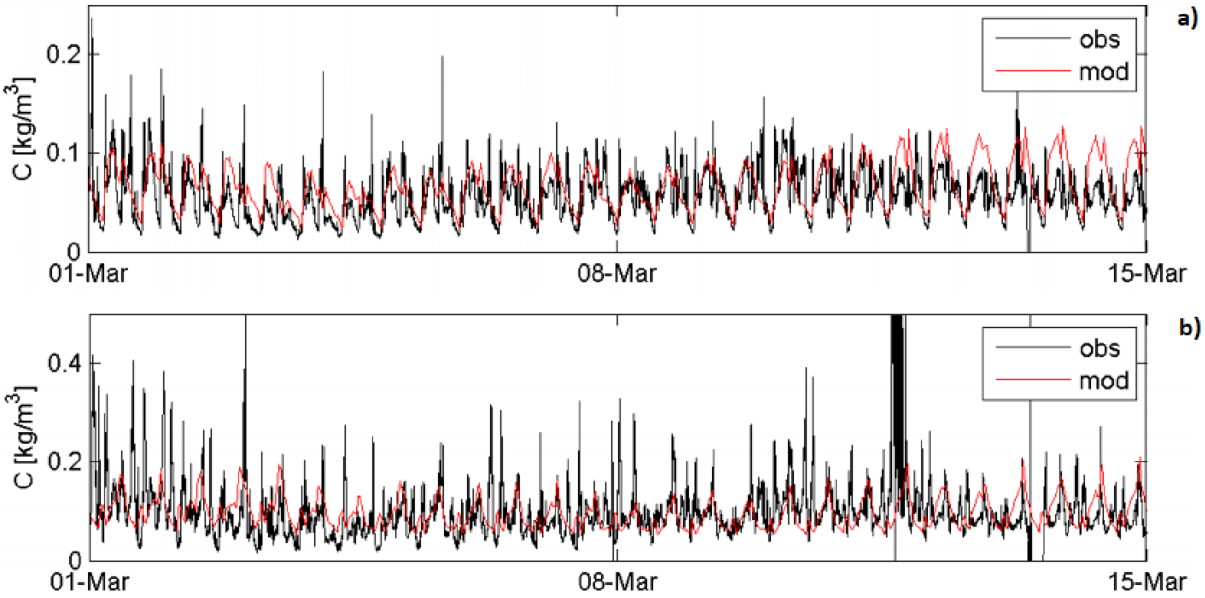


*Figure 19: Observed and modelled suspended sediment concentration in kg/m^3 near the water surface, **a)**, and near the bed, **b)** from the period 1 March to 15 March near the Eemshaven harbor. Taken and adapted from Van Maren et al. (2014).*

Lastly, from personal communications with Groningen Seaports, there is no temperature gradient within the harbor itself (Van Dijken, 2020). The only temperature measurements in the estuary found was done at the Randzelgat, as shown in Figure 20 (Grasmeijer & Pasmans, 2013). Measured at 5 meters below the water surface, the temperature varies between approximately 5°C on 1 March and 10°C on 1 May in 2012 (Grasmeijer & Pasmans, 2013). The available temperature measurements in the Eemshaven harbor show that in March the temperature was 2°C and in May 10°C (Van Dijken, 2020). Therefore, there seems to be no significant temperature difference between the harbor and the estuary.

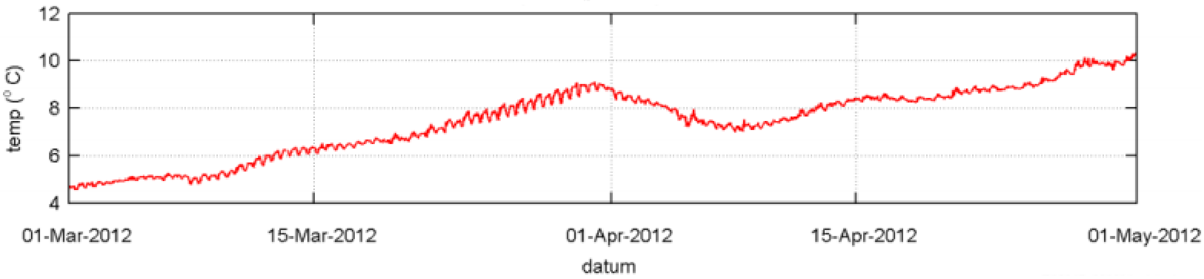


Figure 20: Temperature measured at 5 meters below the water surface at Randzelgat. Taken from Grasmeijer & Pasmans (2013).

Thus, from this superficial comparison, it seems tidal filing and horizontal entrainment are the two most prominent exchange mechanisms. This is also supported by Winterwerp (2005). He classifies four types of water systems where in each system a certain exchange mechanism is most dominant (Winterwerp, 2005). The system resembling the Eemshaven area the most is the “tidal rivers and coastal” (Winterwerp, 2005) area which is an area that is “beyond the fresh-salt water mixing” (Winterwerp, 2005). Subsequently, Winterwerp (2005) and Langendoen (1992) argue that in these types of harbors, the exchange flow by horizontal entrainment and tidal filling are the most prominent exchange mechanisms.

7. SILTATION REDUCTION MEASURES

One of the ways to reduce the necessity for maintenance dredging is reducing the rate of siltation. Harbors can implement several measures during its construction phase to reduce siltation. For example, harbors should be placed in deep waters, have a narrow entrance and the angle of the harbor with respect to the river should be optimized (Rodríguez, 2008). However, in the case of Eemshaven, these parameters cannot be changed. Therefore, this section will analyze structural measures to reduce siltation in the harbor in the existing configuration. First, a general overview of possible measures is given. Second, a selection of measures is made and explained how they function. Third, the siltation reduction as a result of these measures from literature are listed and discussed. Lastly, some sketches of possible configurations of the measures at Eemshaven are presented.

General Overview of Measures

Kirby (2011) analyzed a study undertaken by the Permanent International Association of Navigation Congresses (PIANC) who extensively analyzed measures to reduce siltation in harbors. The measures they analyzed aim to keep the sediment within the estuarine system, the so-called "KSIS (Keep Sediment in the System)" (Kirby, 2013) concept as sediment has a significant ecological value (Bianchini et al., 2019). Therefore, extracting it can disturb the "sensitive estuarine systems" (Kirby, 2013).

PIANC (2008) grouped the possible measures based on how they interact with the sediment:

- Keep sediment moving (KSM)
- Keep sediment out (KSO)
- Keep sediment navigable (KSN)

KSM measures aim at preventing the suspended sediment from settling in the harbor by enhancing the flow velocity with "flow agitation techniques" (Purohit, 2017). This sediment is then ideally removed from the harbor by the natural water flow (Bianchini et al., 2019). KSO measures aim at preventing the sediment of entering the harbor (Bianchini et al., 2019). This can be done by installing an "entrance flow optimisation system (EFOS)" (Kirby, 2011). Lastly, KSN measures, such as an Active or Passive Nautical Depth (Kirby, 2011), involve allowing ships to sail through a certain layer on the bed called a fluid mud layer and thereby reducing the necessity of removing this layer (Kirichek, 2018).

Selection of Measures

The effectiveness of the measures depend on the harbor environment. Kirby (2011) distinguishes four distinct harbor environments which are channels, semi-enclosed basins, impounded docks, and river channels and fairways. Eemshaven is a semi-enclosed basin where the dominant exchange mechanisms are turbulent exchange and tidal filling as determined in chapter 6. As can be seen in equation 1, the siltation rate can be reduced by reducing either the trapping efficiency, which would be a KSM method, or reducing the water exchange and/or sediment concentration in the channel, which is a KSO method (Kirby, 2011). In general, it is difficult to reduce the trapping efficiency p of a harbor (PIANC, 2008). It requires an increase in harbor circulation, or in other words, reducing the residence time of sediment in the harbor, which is usually accompanied by either an increase in the exchange of sediment or a reduction of the harbor volume (PIANC, 2008). Therefore, this study focuses on measures which reduce the exchange rate between harbor and river, Q, and the concentration of sediment, c_a.

Out of the manifold of measures from literature, a selection is made based on proven and quantified results, similarity in harbor system and environment, and the fact that they should not intrude on the current harbor proceedings. For example, narrowing the harbor entrance or reducing basin volume can be effective but are not desirable. For an in-depth and complete overview of all available siltation reduction techniques, see Bianchini et al. (2019), PIANC (2008) and Kirby (2011). Consequently, the following measures have been selected: pile groynes, Current Deflection Wall and sill, and the Passive & Active Nautical Depth.

Pile groynes

A pile groyne consists of a set of poles placed in a row from the coast some distance into the estuary or river (Bianchini et al., 2019) as illustrated in Figure 21. In general, multiple poles are placed with a certain distance between the them, creating permeability, at the upstream part of the entrance perpendicular to the water current (Rodríguez, 2008). Its effectiveness depends on the “shapes, dimensions and location” (Rodríguez, 2008) of the pile groyne and the distance between the poles (Barneveld et al., 2007). Its function is to decrease the velocity difference between harbor and river (PIANC, 2008) and “prevent the formation of large eddies and intercepts the sediment flow” (Bianchini et al., 2019) which otherwise would have reached the harbor. This in effect reduces the mixing layer strength and consequently the exchange of sediment (Rodríguez, 2008). Thus, it reduces the water flow velocity u_r and exchange coefficient f_e from equation 4 and the ambient sediment concentration c_a from equation 1. The downside of installing pile groynes is that sediment accumulates at the poles which still requires removal and that its placement is limited by the navigational routes of ships and other marine activities (Bianchini et al., 2019). Moreover, it could enhance the flocculation of sediment in salt waters which in turn increases the settling of sediment (PIANC, 2008).

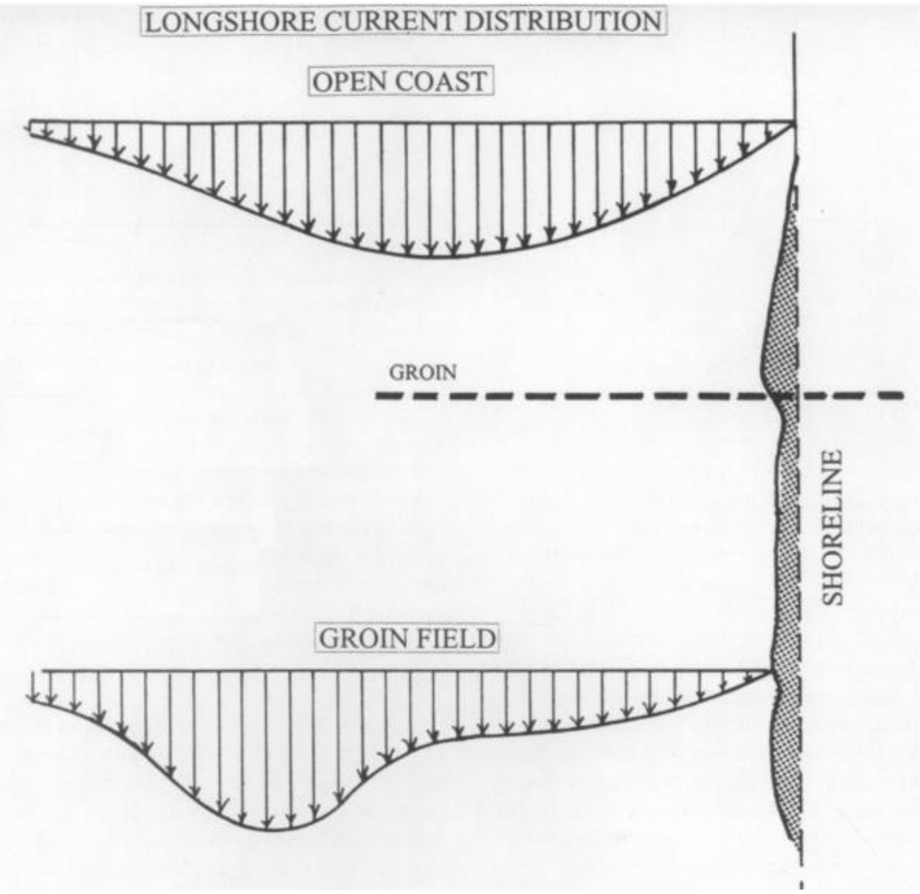


Figure 21: Illustration of the placement of a pile groyne and its effect on the water velocity profile. Taken and adapted from Dette et al. (2004).

Current Deflecting Wall (CDW) and sill

The combination of a Current Deflection Wall (CDW) and sill is called an “entrance flow optimization system” (Kirby, 2011), in short EFOS. The CDW modifies the current flow at the harbor entrance thereby decreasing the strength of the horizontal eddies (Van Maren et al., 2011; Kuijper et al., 2005) and deflects the mixing layer and eddies into the river (Van Maren et al., 2011; PIANC, 2008). This in effect reduces the exchange coefficient f_e, and water flow velocity u_r from equation 4. Additionally, PIANC (2008) explain that a CDW can reduce the exchange coefficient f_d from equation 3 by “inducing a counter flow in the entrance” against the density-driven current. Furthermore, the sill is placed near the bed between the CDW and the coastline (PIANC, 2008). The sill intercepts the near-bed water flow which contains most of the sediment (PIANC, 2008; Kirby, 2011). This reduces the ambient sediment concentration c_a from equation 1 and its exchange with the harbor.

A general depiction of the influence of an EFOS on the horizontal entrainment mechanism is given in Figure 22b which can be compared to the undisturbed mechanism as illustrated in figure 22a. If the design is correct, all tidal filling will take place in the area between the CDW and the coastline rather than through the entrance, which ensures that the sill captures most of the sediment coming from the river (PIANC, 2008). The actual functioning of the CDW depends on the “local hydraulic conditions as well as on the shape and dimensions of the structure in relation to the geometry of the harbor entrance and the total harbor volume” (Kuijper et al., 2005). Kuijper et al. (2005) argue that an important factor in the functioning of a CDW is the total discharge of water from the river through the CDW channel. If this discharge is sufficiently large, the flow at the stagnation zone will be directed into the river rather than into the harbor which reduces the water inflow into the harbor (Kuijper et al., 2005).

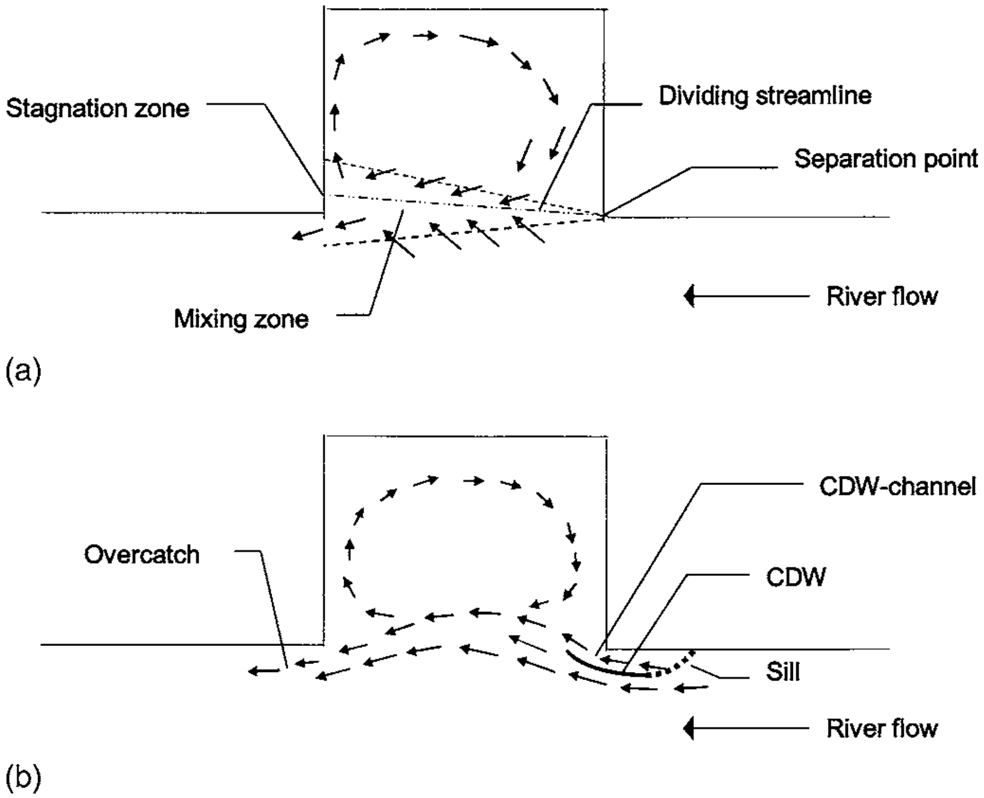


*Figure 22: Illustration of the effect of a CDW on the horizontal entrainment mechanism as illustrated by the altered mixing layer and current flows in the harbor and at its entrance. Undisturbed entrainment effect in **a)** and the effect of the CDW and sill in **b).** Taken from Kuijper et al. (2005).*

Active and Passive Nautical Depth

For safe navigability, harbors limit the entry of ships with a certain draft as not exceeding a certain safe distance between the bottom of a ship and the top of the bed, called UnderKeel Clearance (UKC). This concept is illustrated in Figure 23. However, it has been argued by multiple studies that in harbors where the bed has certain properties, the UKC can be lower or even negative (Verwilligen et al., 2014). This means that the limit can be set lower or that ships can even sail through this layer of mud. In this case, the mud is called a fluid mud and it is proposed that ships can navigate through this layer. This concept can reduce the need for maintenance dredging and even allow larger ships to enter the harbor.

Fluid mud is a “visco-elastic fluid” (Kirichek, 2018) which consists of a high concentration of suspended sediment in combination with “microbial slimes” (Kirichek, 2018) and for the most part water (Wurpts, 2005). Furthermore, it is a “pre-stage to mud or silt” (Wurpts, 2005). Already in the 1980’s, several experiments illustrated that up to a certain density, the fluid mud is navigable (Kirichek, 2018). This depth was termed the Nautical Depth (Kirichek, 2018). The Nautical Depth is defined as: “the level where physical characteristics reach a critical limit beyond which contact with a ship’s keel causes either damage or unacceptable effects on controllability and manoeuvrability” (Kirichek, 2018). Or in other words, it is the “vertical distance between the nautical bottom and the undisturbed free water surface” (Kamphuis et al., 2013). The Nautical Depth criterium can be both active or passive. In the passive sense, it simply means that through measurements, the physical characteristics, or “rheological parameters” (PIANC, 2008) of the bed in a harbor are mapped out and if it conforms to a certain threshold value through which ships can safely sail, it does not have to be dredged (PIANC, 2008; Kirby, 2013). The most important rheological parameter is the yield stress which is related to the viscosity of the mud (Kamphuis et al., 2013). At Emden for example, a maximum yield stress of 100 Pa is taken as the threshold value (Kamphuis et al., 2013).

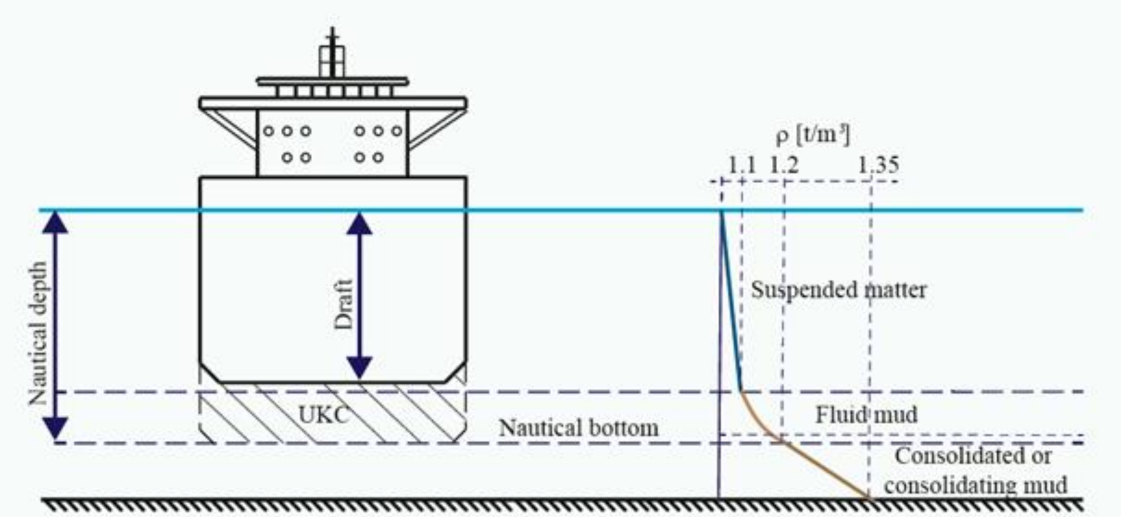


Figure 23: Illustration of the Nautical Depth method. UKC stands for UnderKeel Clearance (Barth et al., 2016). The consolidated or consolidating mud is also referred to as hard bottom (Barth et al., 2016). The density of the particular layers is indicated to the right. Taken and adapted from Kirichek (2018).

In an Active Nautical Depth method, the bed is “engineered” (PIANC, 2008) and maintained into this fluid mud state. This engineering can be done by physical or “chemical and microbiological” (Kirby, 2011) manipulation. An example of physical manipulation is a “Water Injection Dredger” (Kirby, 2013) where a certain part of the bed is fluidized (Kirichek & Rutgers, 2020). The downside of this method is that this process has to be repeated after about three weeks (Kirby, 2013). Additionally, using this method, the fluidized mud can also be transported to a sediment trap through natural currents or other measures to reduce the need for dredging as well. An example of chemical and microbiological manipulation is in-situ conditioning which involves the "manipulation of the chemical and microbiological climate in the mud" (Kirby, 2013) by oxygenating the mud layer which can increase the time the mud remains in a fluid form from several weeks to months (Kirby, 2011).

Results of siltation reduction measures at other harbors

In this section, the modelled, analyzed and implemented siltation reduction measures from literature are presented and explained. Harbors which are comparable to the Eemshaven are included. This means that the harbor must be a semi-enclosed harbor, located at a tidal river. The results are related to the dominant exchange mechanisms present at the harbor. The exchange mechanisms are labeled 1 to 3 as listed in chapter 6. To reiterate, the harbor-river exchange mechanisms are:

1. Tidal filling
2. Density driven currents
3. Horizontal entrainment (turbulent mixing layer)

Table 2: Overview of the relevant literature accompanied by the exchange mechanisms, mitigation measures and results.

Source	Exchange mechanism(s)	Mitigation measure(s)	Siltation reduction
El Hamdi, 2011	1,2,3	CDW	15-22%
Barneveld et al., 2007	3	Sill and screen	25%
Van Maren, 2011	1,2,3	CDW and sill	18%
Decrop, 2013	1,2,3	CDW	10-20%
Kuijper, 2005	1,3	CDW and sill	40-55%
Van Schijndel & Kranenburg, 1998	1,3	Pile groyne	53%
Kirichek & Rutgers, 2020	-	Active Nautical Depth	0.2 – 0.4 Million m^3 of dredge
Kirby, 2013	-	Active Nautical Depth	100%
Kamphuis & Meinsma, 2013	-	Passive Nautical Depth	10%

First, El Hamdi (2011) modelled several possible measures including several setups of a CDW with and without a sill to reduce the exchange flows at the Botlek harbor in Rotterdam. He found that tidal filling and horizontal exchange are the predominant exchange mechanisms but that density currents still contribute 10% to the exchange measured over a tidal cycle (El Hamdi, 2011). El Hamdi (2011) found that the configuration of the CDW is vital for its efficiency as the CDW can affect the siltation both positively and negatively as the exchange mechanisms are extremely sensitive to the specific design. Two variants of the CDW were quite promising leading to 22% and 15% reduction of the exchange flow (El Hamdi et al., 2011).

Second, Barneveld et al. (2007) discuss multiple options for reducing siltation in a harbor situated at a tidal river. They analyze one promising option in detail, namely an upstream, near-bed sill and screen (Barneveld et al., 2007). Their setup is illustrated in Figure 24.

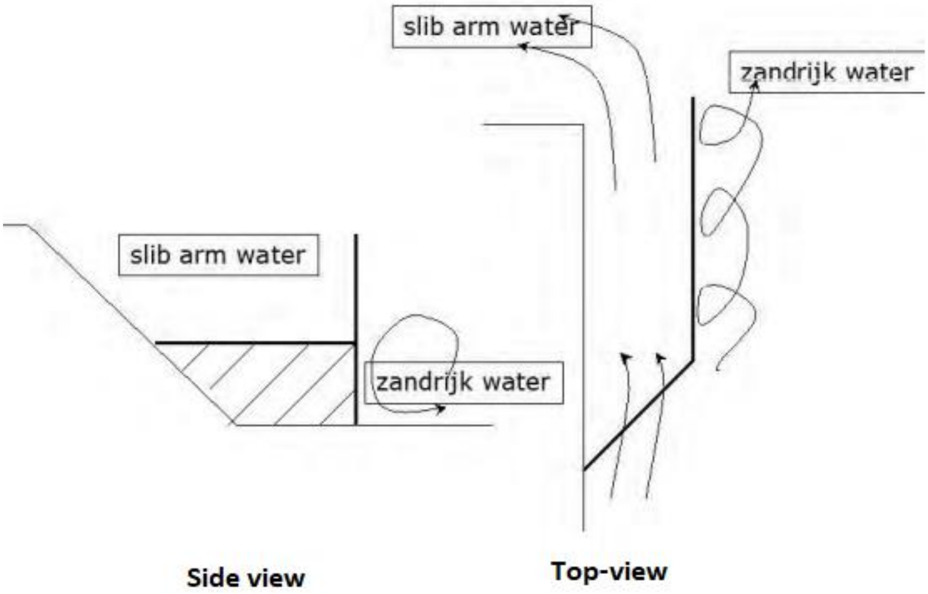


Figure 24: Design of the sill with screen with both a side view and top view. Translation of the Dutch terms: slib arm water = water with low silt content, zandrijk water = water with high sand content. Taken from Barneveld et al. (2007).

Barneveld et al. (2007) argue that in this setup, relatively silt-poor water near the surface will pass across the sill into the harbor whilst silt-rich and sand-rich water near the bed will be pushed away from the harbor entrance due to the sill and screen. The sill sits at a 45° angle with respect to the shore and the screen runs parallel to the shore (Barneveld et al., 2007). They expect a reduction in dredge volumes of 25% (Barneveld et al., 2007).

Third, Van Maren et al. (2011) designed a CDW and sill setup resting on permeable poles at the Deurganckdok. They found that the CDW deflects a "near-bed horizontal eddy towards the Scheldt River" (Van Maren et al., 2011) in addition to lowering the flow velocity in the eddy by half and reducing the sediment concentration (Van Maren et al., 2011). Additionally, the sill reduces the "density-driven near-bottom inflow" (Van Maren et al., 2011) as it re-directs the water flow near the bottom, with higher sedimentation concentration, toward the river (Van Maren et al., 2011). They found that their design leads to an 18% decrease in sedimentation in the Deurganckdok (Van Maren et al., 2011). Noteworthy, changing this design by either widening the CDW channel by placing it 15 meters further into the river or lowering the sill by 3 meters leads to 4% and 2% more sediment deposition in the harbor respectively (Van Maren et al., 2011).

Additionally, following the numerical simulations of the CDW by Van Maren (2011), the CDW was constructed, as illustrated in Figure 25, and Decrop (2013) started to analyze field measurements to assess the effect of the construction.

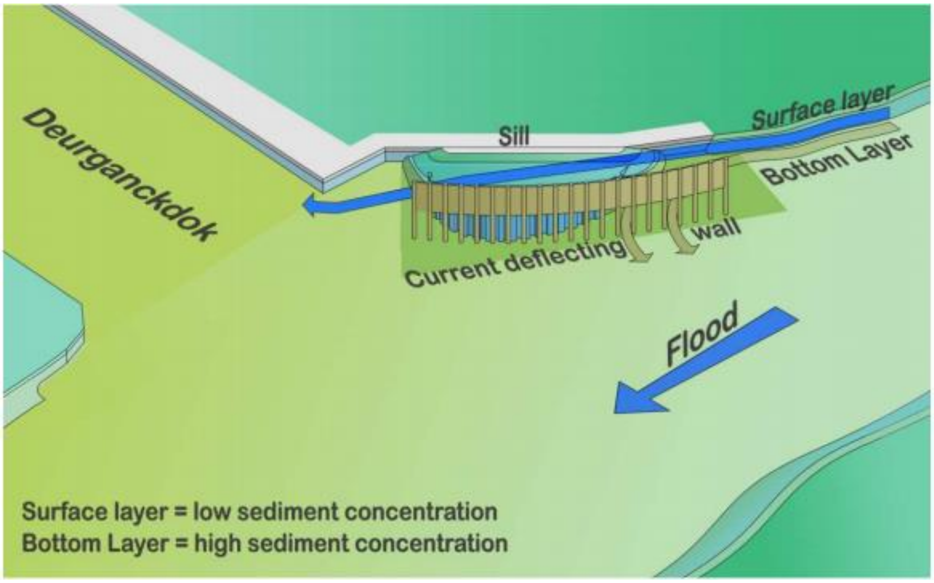


Figure 25: Illustration of the CDW and sill construction at the Deurganckdok. Taken from Decrop (2013).

They found that the CDW setup reduced the intensity of density currents and eddy formation which leads to an expected reduction in siltation of 10-20% (Decrop, 2013). However, they found it difficult to analyze the effect of the CDW and sill as there were multiple structural changes around the harbor which could have affected the siltation rate as well (Decrop, 2013).

Similarly, at the harbor in Hamburg, a CDW was built in 1991 near the Köhlfleet basin to minimize siltation (Kuijper et al., 2005). At this harbor, horizontal entrainment, tidal filling and possibly sediment-induced density currents cause the exchange of water and sediment (Kuijper et al., 2005). Their design of a CDW and sill is displayed in Figure 26 below. This has resulted in a dredge reduction of 40% (Kuijper et al., 2005). Subsequently, Kuijper et al. (2005) analyzed whether a CDW and sill could reduce siltation at the Parkhafen basin as well using a scale model. In Parkhafen, density currents occur due to a difference in suspended sediment concentration between the river and harbor (Kuijper et al., 2005). They found that the combination of a CDW and a sill can reduce the siltation with 40-55% (Kuijper et al., 2005).

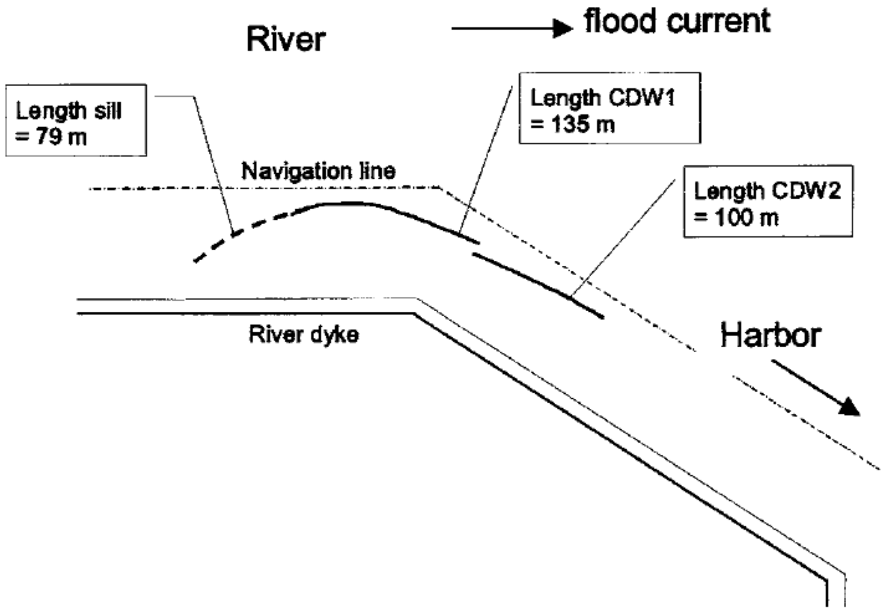


Figure 26: Illustration of the designed and implemented CDW and sill at Parkhafen, Hamburg. Taken from Kuijper et al. (2005).

Then, Van Schijndel & Kranenburg analyzed multiple measures in a physical scale model and measured the reduction of the exchange coefficient. They analyzed multiple sill configurations, a dam and a pile groyne field. The most relevant and promising result from their modelling is the pile groyne field. Their specific configuration of an upstream permeable pile groyne field reduces the exchange by 53% (Van Schijndel & Kranenburg, 1998). This is due to the fact that the pile groyne field prevents the development of eddies in the mixing layer which reduces the velocity in the eddies within the harbor which reduces the siltation in the harbor (Van Schijndel & Kranenburg, 1998).

Subsequently, the Active Nautical Depth method using the Water Injection Dredging (WID) technique has been applied in a pilot project at the Calandkanaal in the Rotterdam harbor (Kirichek & Rutgers, 2020). In addition, a sediment trap to capture the fluidized mud was constructed as well (Kirichek & Rutgers, 2020). After applying the WID, they measured the physical parameters of the fluid mud layer, such as density and yield stress, every week (Kirichek & Rutgers, 2020). This was done to assess the effect of the WID and the subsequent settling and consolidation rates of the created fluid mud (Kirichek & Rutgers, 2020). The pilot showed that the required maintenance dredging was reduced by approximately 0.2-0.4 million m^3 (Kirichek & Rutgers, 2020). Additionally, this method led to an extension of the necessity for maintenance dredging by 2 months (Kirichek & Rutgers, 2020). Therefore, this initial pilot seems promising. Additionally, Kirby (2013) explains that the application of the Active Nautical Depth through in-site conditioning at Emden has resulted in a reduction of annual maintenance dredging from 4 million to 0 tonnes with an additional reduction in annual costs from 12.5 million to 4 million euros.

Lastly, a pilot study which analyzed the possible reduction in dredging using the Passive Nautical Depth at the harbor in Delfzijl has been described by Barth et al. (2016), Kamphuis et al. (2013), Verwilligen et al. (2014) and Kamphuis & Meinsma (2013). Simulations were performed for very small and negative UKC, which means that ships sail close to the fluid mud layer and even through it (Verwilligen et al., 2014). Verwilligen et al. (2014) varied the density, viscosity and thickness of the muddy layer in the simulation. They found that safely navigating a vessel at different depths above and through the fluid mud layer depends on the speed of the vessel and the specific physical and rheological characteristics in the harbor (Verwilligen et al., 2014). To relate this to the specific environment of Delfzijl, they performed a pilot study. Some initial and tentative results showed that with a UKC of -7%, a reduction of 10% of maintenance dredging can be achieved (Kamphuis & Meinsma, 2013).

Design Proposition

Subsequently, taking the siltation reduction at the other harbors into account, a rough sketch of what the proposed designs at the Eemshaven could look like are presented. This is done to illustrate the scale of the measures and their rough positions relative to the harbor entrance.

Current Deflection Wall and Sill

The sketch of the CDW is based on Van Maren et al. (2011), Van Rijn (2016), and Kuijper et al. (2005). Van Maren et al. (2011) explain that the CDW wall at the Deurganckdok is placed at a depth of 6.75m up to the surface resting on piles. However, they do not specify the length of the CDW. Van Rijn (2016) explains that the length of a CDW should be between 30-40% of the entrance width. With an entrance width of 470 meters (Groningen Seaports, 2020), the length of a CDW should be between 140-190 meters. Additionally, the CDW channel width is a very important parameter (Kuijper et al., 2005). Determining this width, and thus distance from the breakwaters at the Eemshaven entrance, usually presents a conflict between sediment exchange reduction and accessibility of the entrance for ships (Kuijper et al., 2005). Van Rijn (2016) argues that the width of the CDW channel should be around 10-15% of the river channel width. Subsequently, the EFOS measures are often placed on the sea-side of the entrance as during flood there is a “superposition of tidal filling and wake formation, which act together to fill the basin” (PIANC, 2008). However, sometimes these structures are also necessary on the other side of the entrance as the ebb flow might not be strong enough to pull the mixing layer out of the harbor entrance (PIANC, 2008). The rough sketch is illustrated in Figure 27 below. It is worth noting that the area between the sill and the coast is a sandbank. Therefore, the water flowing into the harbor will cross the sill, contrary to what the picture below might suggest.

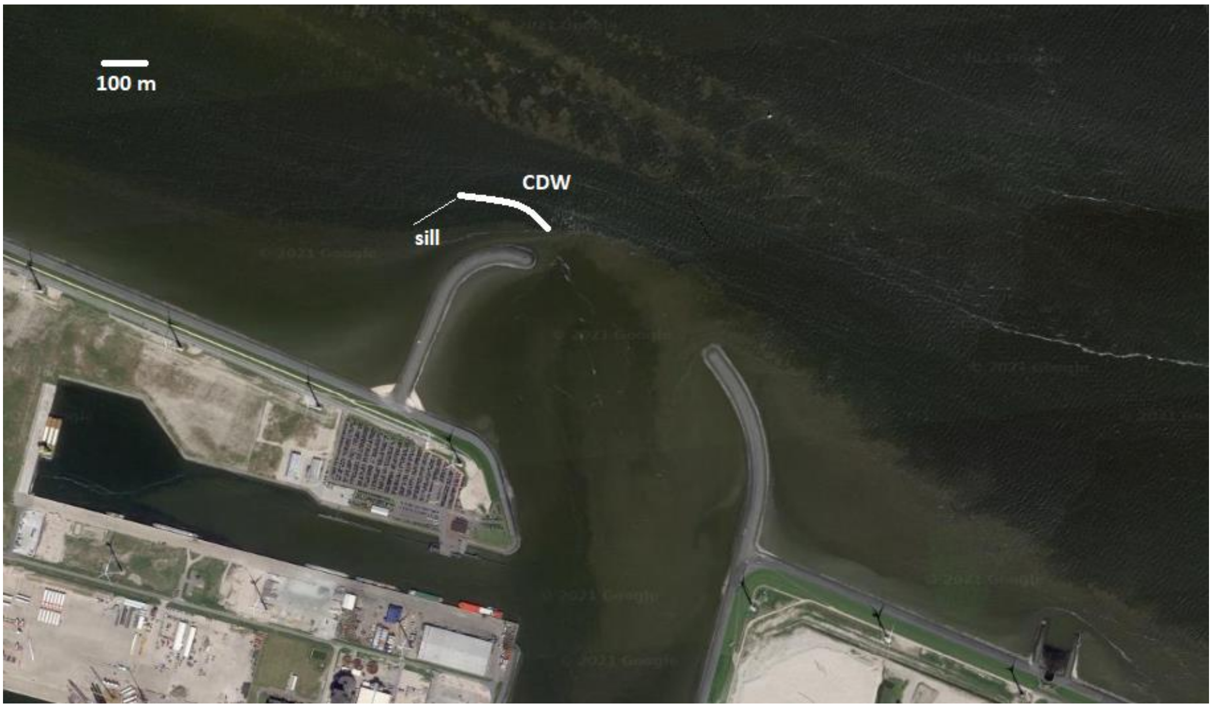


Figure 27: Rough sketch of the CDW and sill. Picture taken and adapted from Google Earth.

Pile groynes

Van Rijn (2016) lists some design criteria for optimal use of pile groynes: the length of the pile groyne field should be larger than 25% of the harbor entrance width, it should be placed at a distance about 10%–15% of the harbor entrance width from the upstream edge, and the distance between the individual poles should be increasing from 0 meters at the shore to one pole width at the end of the groyne. The width of the harbor entrance is 470 meters (Groningen Seaports, 2020). Therefore, the length of the pile groynes should be at least 118 meters at a distance of 47-70 meters from the entrance. The sketch is illustrated in figure 28 below. Additionally, the angle is based on a study by Van Schijndel & Kranenburg (1998) who placed their permeable pile groynes at a 90° angle with respect to the river bank.

Figure 28: Rough sketch of the pile groynes. Picture taken and adapted from Google Earth.

Passive/Active Nautical Depth

The location of the Water Injection Dredger pilot at the Calandkanaal was chosen based on some preliminary conditions in that harbor (Kirichek & Rutgers, 2020). For example, the sediment consists mostly of “fine cohesive minerals forming mud layers” (Kirichek & Rutgers, 2020) in the harbor. Additionally, the fluid mud must be high in organic and low in sand content (PIANC, 2008). Wurpts (2005) argue that these methods can be applied where sediment has “a sand content of up to 10% with grain sizes between 60 and 200 µm”. However, with higher sand contents there is lower organic content which increases the viscosity (Wurpt, 2005). Therefore, for this measure to be successful, in-depth knowledge of the characteristics of the bed are vital.

8. DISCUSSION & ADVICE

In this section, significant gaps and possible points of improvements are given, the most important results of the research are discussed, and advice is given to Groningen Seaports and TAUW on how to utilize the results from this research in a follow-up research.

General Discussion

A considerable issue in reproducing and applying sediment reduction measures as applied in other harbors is that the design is highly dependent on the local environment (PIANC, 2008). The specific designs in the literature have often been achieved following numerous detailed simulations, physical scale models and even actual implementations. Therefore, the reduction in siltation as reported in table 2 can only be used as an indication of the possible effectiveness at the Eemshaven. This is also illustrated by the fact that different harbors, implementing similar measures, have different reductions in siltation. These differences can possibly be explained by the dependence of the effectiveness of a measure on "local idiosyncrasies" (Kirby, 2011) which includes harbor configuration and the local environment. For example, both at the Deurganckdok (Van Maren et al., 2011; Decrop, 2013) and at Hamburg (Kuijper, 2005), a CDW and sill is placed. However, this resulted in a different reduction in siltation as can be seen in table 2. Van Maren et al. (2011) found a reduction in siltation of 18% while Kuijper (2005) found a reduction between 40-55%. The Deurganckdok is situated in a macro tidal estuary near the Estuarine Turbidity Maximum, with a suspended sediment concentration between 200-1000 mg/L near the surface and bed respectively (Van Maren et al., 2011) and with large horizontal and vertical gradients in salinity (Decrop, 2013). Similarly, even though the harbor of Hamburg lies at a tidal river as well, the suspended sediment concentration between 25-100 mg/L is significantly different than at the Deurganckdok (Kuijper, 2005). The high suspended sediment concentration at the Deurganckdok might make the sill less effective compared to the situation at Hamburg as more sediment is able to circumvent the sill. Therefore, significantly detailed modelling is required to analyze the sensitivity of these measures on the environment. Overall, the amount of literature on siltation reduction measures is rather scarce and moreover does not provide an overarching blueprint for harbor companies to readily implement.

Furthermore, it should be analyzed how effective the Active and Passive Nautical Depth method can be at the Eemshaven. The reduction in siltation due to the Nautical Depth method as applied to Emden and Delfzijl might not be as effective at Eemshaven as the harbors are situated at different positions in the Ems estuary as shown in Figure 1. The physical mechanisms such as tidal range, water flow velocities, salinity, and suspended sediment concentration are different at Emden and Delfzijl than at the Eemshaven as can be seen in chapter 5. It is therefore important to assess whether the Nautical Depth measure is influenced by these factors and how much or whether its effectiveness is independent from the local environment. Additionally, in-depth analysis of the physical and rheological properties of the mud in the harbor are vital. To establish whether or not the mud in a harbor can be termed fluid mud, measurements on the "grain size distribution, water content, organic content, density, and specific weight" (Verwilligen et al., 2014) are necessary. Additionally, Barth et al. (2016) explain that the resistance, or shear stress, of the mud is also important which is represented by the "yield point and dynamic viscosity" (Barth et al.). These parameters can influence the behavior of a sailing vessel if it comes into contact with the mud but also when it is close to it (Verwilligen et al., 2014).

Subsequently, a more in-depth analysis of the exchange mechanisms and their interaction between the Eemshaven harbor and the Ems estuary, as discussed in chapter 6, is necessary to model the effects of the measures. More research into the tidal filling and horizontal entrainment exchange mechanisms is necessary. This study has provided a qualitative basis by presenting the tides as displayed in Figure 18 and the current flow velocities at the harbor entrance as displayed in Figure 16, 17, and 18. However, this study has found no reference to assess the magnitude of the interaction between the mechanisms based on this data. Additionally this study has found no data on the suspended sediment concentration within the harbor. As density-induced currents due to suspended sediment concentration differences between the harbor and the estuary can have significant effect on the siltation rate in the harbor (Winterwerp, 2005), it is vital to obtain this.

Environmental and economic assessment

Then, as the aim of this study is to limit anthropogenic interventions in the estuary and its effect on the estuarine system, the environmental effects of the implemented measures should be analyzed. Arguably, the CDW, sill and Active Nautical Depth measures remove a sediment sink from the estuarine system. The CDW and sill deflect the sediment into the estuary and the Active Nautical Depth method as applied in Emden in essence blocks sediment from entering the harbor as well (Kirby, 2011). As the suspended sediment concentration is an important ecological parameter in estuaries, the effects of the measures on this parameter should be analyzed. Furthermore, an economic assessment of the measures must be made. This analysis must compare the costs of traditional dredging with the costs of installing and maintaining the implemented measures including the avoided dredging costs. The research in this field is quite scarce and only a succinct economic assessment of some measures can be found in Bianchini et al. (2019).

Alternative measure

In view of the protected status of the Ems estuary, it might be fruitful to investigate possibly more environmentally friendly measures. These measures are not included in this study as there were no quantified results. One of the approaches which has been applied to other harbors in the Netherlands is the Working With Nature approach by Ecoshape. EcoShape is a company consisting of private companies, government organizations, universities and other parties which focuses on decreasing siltation rates and increasing harbor development in the Wadden Sea whilst “at the same time enhancing the ecological state of the harbor and its direct surroundings” (Baptist et al., 2017). Each solution is made with the Working With Nature approach in mind. This is that it either uses nature “as part of the engineering solution” (Baptist et al., 2017) or the solution “provides opportunities for extra ecosystem services” (Baptist et al., 2017). They propose three general solutions with the aim of decreasing siltation rates, namely creating salt marshes, creating estuarine gradients, and optimizing flow patterns (Baptist et al., 2017). These solutions have been investigated for the harbors of Harlingen, Den Helder and Delfzijl. A promising measure for the Eemshaven environment is the creation or stimulated development of a salt marsh near the harbor. This can reduce the siltation rate in a harbor, reduce suspended sediment concentrations and improve the ecosystem (Baptist et al., 2017). For example, at the Harlingen harbor, Baptist et al. (2017) propose dumping the dredged material at a location where it will flow to a salt marsh nearby, the so-called Mud Motor. This salt marsh can then act as a sediment sink which prevents the sediment from flowing toward the harbor while it also functions as an important ecosystem (Baptist et al., 2017). Furthermore, TAUW and Groningen Seaport already did some preliminary studies on the possibilities of capturing the silt using a so-called dredge-buffer and a salt marsh (Hubbeling, 2020). Therefore, the results from their studies can be used to model these measures. However, similar to the issues raised in the previous section, the effects of adding a sediment sink to the system by adding the salt marsh or dredge-buffer and the unknown effects of redistributing the dumped dredge on the local hydrodynamics and suspended sediment concentration are important to analyze in more detail.

Advice to Groningen Seaports

This study advises that a follow-up modelling research prepares different scenarios with different combinations and configurations of a CDW, CDW and sill, pile groynes and the previously mentioned alternative measures in order to analyze the effectiveness in terms of siltation reduction but also the costs and environmental effects of these constructions. Additionally, Groningen Seaports can use their previous project with TAUW on the creation of salt marshes and dredge-buffers in reducing the silt reaching the harbor. The modelling research can use the qualitative data on the estuarine environment and its interaction with the Eemshaven harbor from chapter 5 and 6 as input, validation, and calibration of the model. For this modelling research, Groningen Seaports could work together with the TU Delft and Deltares. They have an immense research database and their own modelling tools. Many of the literature used in this research used studies produced by these two institutions. The follow-up modelling research must be able to accurately represent the local environment, harbor geometry and specifics of the implemented measures. It should assess the actual position and scale of the proposed design given in 7 based on the local hydrodynamics.

Furthermore, it might be fruitful for the modelling research to look into different dredging and disposal activities. For example, Hendriks & Schuurman (2017) performed a study on the return flow of the dumped sediment around the harbor at Rotterdam. They found that the siltation at the harbor consists of 36% return flow of the previously dumped silt (Hendriks & Schuurman, 2017). It might be possible that the disposed dredged materials might return to the Eemshaven over time. To analyze this, the transport of the dredged materials from the disposal sites must be modelled. It might be possible that disposing the dredged materials at different locations or different times of the year might reduce the siltation rate at the Eemshaven.

9. CONCLUSION

This study analyzed the most important natural factors shaping the sediment dynamics throughout the Ems estuary and the mechanisms determining the siltation rate at the Eemshaven harbor qualitatively. Subsequently, based on actual implementations and previous physical and numerical modelling of siltation reduction measures in comparable harbors, there are three measures from literature which have the potential to reduce the siltation at the Eemshaven harbor. First, a Current Deflection Wall can reduce the siltation between 15-22% and combining it with a sill can reduce it between 18-55%. Additionally, the construction of pile groynes has resulted in a reduction of 53%. Lastly, a pilot at Delfzijl showed that with the Passive Nautical Depth method a reduction in siltation of 10% can be achieved and with an Active Nautical Depth method as applied at Emden a 100% reduction can be achieved. Thus, to repeat the main research question: what can be effective measures to reduce maintenance dredging at the Eemshaven harbor? Each of these measures can potentially be effective. However, this depends considerably on the local environment and harbor design. Therefore, a follow-up modelling research must be done in order to analyze whether these measures can in fact be effective. This research can use the obtained qualitative data as input but also to validate and calibrate the model.

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