Maintenance dredging in the Port of Rotterdam

A research to the increase in maintenance dredging volume at Port of Rotterdam

by

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Abstract

The Port of Rotterdam (PoR), located in the Rhine-Meuse estuary, is subject to sedimentation. In order to keep the port accessible for vessels with high drafts, maintenance dredging works are done. The maintenance dredging over the port area is executed by two parties, PoR itself regarding the harbour basins and Rijkswaterstaat (RWS) regarding the river and waterways.

Since 2013 a substantial increase of the yearly total maintenance dredging volume of the area under control of PoR is observed. The problem of this research is the increase in maintenance dredging volume, from an average of 5.2 mln cubic meters a year (over 2005-2012) to an average of 8.9 mln cubic meters a year (over 2013-2016). By analysis of the administrated maintenance dredging volumes database of PoR it is concluded that the problem is concentrated at Maasvlakte I. Including the maintenance dredging volumes data of RWS results in the conclusion that over the entire port area no occurrence of an increase in maintenance dredging volume is observed. A decrease administrated by RWS at the same period of time is concentrated at the area in front of Maasvlakte I, the harbour basin responsible for the increase in maintenance dredging volume of PoR. These findings lead to the conclusion that not an increase of sedimentation over the port area is responsible for the research problem, but a redistribution of the sedimentation rates from the area in front of Maasvlakte I to Maasvlakte I is.

An analysis of the events that are potentially of influence on the research problem is performed. Based on the correlation of time and potential impact on the hydrodynamics of the water system, the event 'Construction of Maasvlakte II' is selected for an assessment. Two simulations with an extensive hydrodynamic flow model managed by PoR are run. One simulation includes the layout of the Maasvlakte before the construction of Maasvlakte II, the other includes the layout of the Maasvlakte as it is today. Both simulation use exactly the same initial and boundary conditions. With use of the simulations, the impact on the hydrodynamic conditions within the area of interest is assessed. The results show a significant increase of the tidal filling volume of the Maasvlakte harbour basins with a factor of 1.4. This increase is associated with in particular a significant increase of the horizontal flow velocities, and strengthened by a higher horizontal density gradient as a result of higher mixing rates of fresh and saline water at the Maasvlakte. The increase of the horizontal flow velocity is in particular measured in front of Maasvlakte I and in the connection to Maasvlakte I itself. Within the Maasvlakte harbour basin, the velocities are quickly dampened by the large width of the basin.

The results of the assessment correspond accurately with the results of the data analysis. At the area subject to an increase of the horizontal flow velocity, a decrease of the maintenance dredging volume is observed. At the area where an increase in maintenance dredging volume is observed, no to slight changes of the flow velocity are measured. This is explained as follows. The increase of the tidal filling volume by the construction of Maasvlakte II, results in an increase of the horizontal velocities over the entire area connecting the North Sea to the Maasvlakte. Sediments that were able to settle within that connection before are now kept in suspension and transport to the Maasvlakte. The sediments kept in suspension reach the harbour basins where the horizontal flow velocities are quickly dampened by the large width of the basin, enabling the sediments to settle.

It is concluded that the dominant mechanism leading to the increase in maintenance dredging volumes at the Port of Rotterdam is a change in local hydrodynamics by the construction of Maasvlakte II, resulting in a redistribution of the sedimentation rates within CaBe-system. A potential reduction measure in the form of a sediment trap is recommended to improve the current situation, but is unable to bring the hydrodynamics within system back to the situation as before the construction. The research problem is one of the consequences of the construction of Maasvlakte II, and hence partly have to accepted as well. A detailed study to the design of the problem specific sediment trap is required. Other studies that are recommended to improve the understanding of the actual problem regard the used dredging strategy, the exact pattern of sedimentation and the development of the composition of the bed material in the area the problem is concentrated.

Preface

In front of you is the report of the thesis research that I conducted at Port of Rotterdam Authority, as a conclusion of the MSc. degree in Hydraulic Engineering specialization in Ports and Waterways at Delft University of Technology.

During the writing of this thesis I was guided by my graduation committee: Tiedo Vellinga (Professor Ports and Waterways at Delft University of Technology), Bas van Maren (Researcher at Delft University of Technology), Bas Wijdeven (Lecturer Ports and Waterways at Delft University of Technology) and Gijsbert Kant (Project Manager at Port of Rotterdam Authority). I would like to thank them for their useful input during the meetings and guidance during the entire process.

I would like to thank the employees at Port of Rotterdam Authority for their interest and help during my research. Finally, I would like to thank my family and friends for their support during my studies and the writing of this report.

L.H. de Bruijn
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Contents

List of Figures

Nomenclature

Abbreviations

BL	Botlek
ETM	Estuarine turbidity maximum
EUP	Europoort
EW	Eemhaven-Waalhaven
FH	Fruithaven
HoH	Hook of Holland
MD	Maintained depth
mln	Million
MV	Maasvlakte
MV1	Maasvlakte I
MV2	Maasvlakte II
OSR	Operationeel Stromingsmodel Rotterdam (translation: operational flow model Rotterdam)
PN	Pernis
PoR	Port of Rotterdam
RWS	Rijkswaterstaat
SH	Stadhaven
SPM	Suspended particulate matter
tds	Tons dry solids

1 Introduction

The Port of Rotterdam (PoR), located in the Rhine-Meuse estuary, is the largest and busiest port in Europe. Shipping transport is a worldwide growing industry and vessels are increasing in size to meet the demand of supply. This results in higher ship drafts. In order to keep the port accessible for all type of vessels, maintenance dredging work is done.

The Rhine-Meuse estuary is the transition zone between a river environment (Rhine and Meuse flowing in in the east) and a maritime environment (adjacent to the North Sea in the west), and is subject to influences of both. Both environments cause a sediment transport, respectively seaward and landward. These sediment fluxes converge somewhere within PoR, resulting in high sedimentation rates.

The high sedimentation rates are problematic for the navigability of the fairways. To ensure the maintained depth (MD), which is the navigable depth guaranteed by PoR, two survey vessels are full-time monitoring the current depths within the entire PoR. Subsequently dredging vessels are directed to critical areas to perform maintenance dredging, which is a continuous task. Contaminated dredged material has to be disposed at the Slufter, a large scale disposal site in the south west of the port closed from the open water. Redistribution in the water system is allowed for the major part of the material dredged at the port areas and is done by disposing at the North Sea at an area called Loswallen, approximately seven kilometres away of the harbour mouth. Part of the dredging material disposed at the Loswallen is transported back to the harbour mouth by a return current influenced by North Sea conditions [Hendriks and Schuurman, 2017]. The entire cycle from dredging to disposal form the activity referred to as maintenance dredging activity. An overview of the sediment fluxes of the system PoR is part of is given in Figure 1.1.

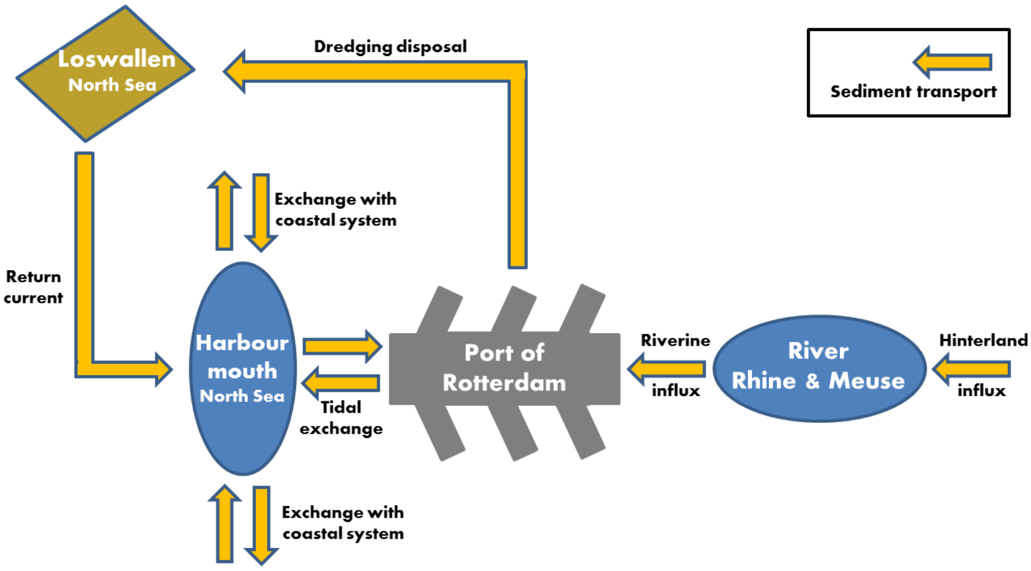

Figure 1.1: Overview of the sediment transports in the system PoR is part of

1.1. Problem definition

Since 2013 a substantial increase of the yearly total maintenance dredging volume of PoR is observed, which is shown in Figure 1.2. This increase will be analysed in detail later in this report. However, because this data also provides the motivation for this study it is shortly discussed here.

This research makes distinction between two periods, one from 2005 to 2012 which will be referred to as the *base period*, and the years from 2013 to 2016 which will be referred to as the *problem period*. During the base period the yearly average total maintenance dredging volume of PoR was 5.2 million cubic metres, which increased to 8.9 million cubic metres over the problem period with a maximum until today of 11.3 million cubic metres in 2016. With use of the data analysis it is found that Maasvlakte I (MV1) is the dominant responsible harbour basin for the strong increase in maintenance dredging volume. For that reason the focus of research is on the Maasvlakte-area[1] (MV-area), further substantiation is found in Chapter 3.

During the last decade PoR experienced several events[2], which might be responsible for the increase in maintenance dredging volumes observed at MV1. Distinction is made between internal events (human influenced, such as adjustments to port layout or geometry) and external events (nature driven, such as deviations in weather and climate patterns). A change in dredging volumes caused by several events was expected, but not of the order of magnitude observed in the last couple of years. The underlying mechanisms are insufficiently understood and require further research. Knowledge on this subject is of great (financial) value to PoR and for that reason it indirectly is a problem that concerns the Dutch society in the form of the tax system.

[1]This report will refer to MV1, MV2 and the adjacent areas Caland- and Beerkanaal as the Maasvlakte-area

[2]This report will use the term ‘event’ for all physical changes, and deviations to regular weather and hydraulic conditions with a potential influence on the maintenance dredging development.

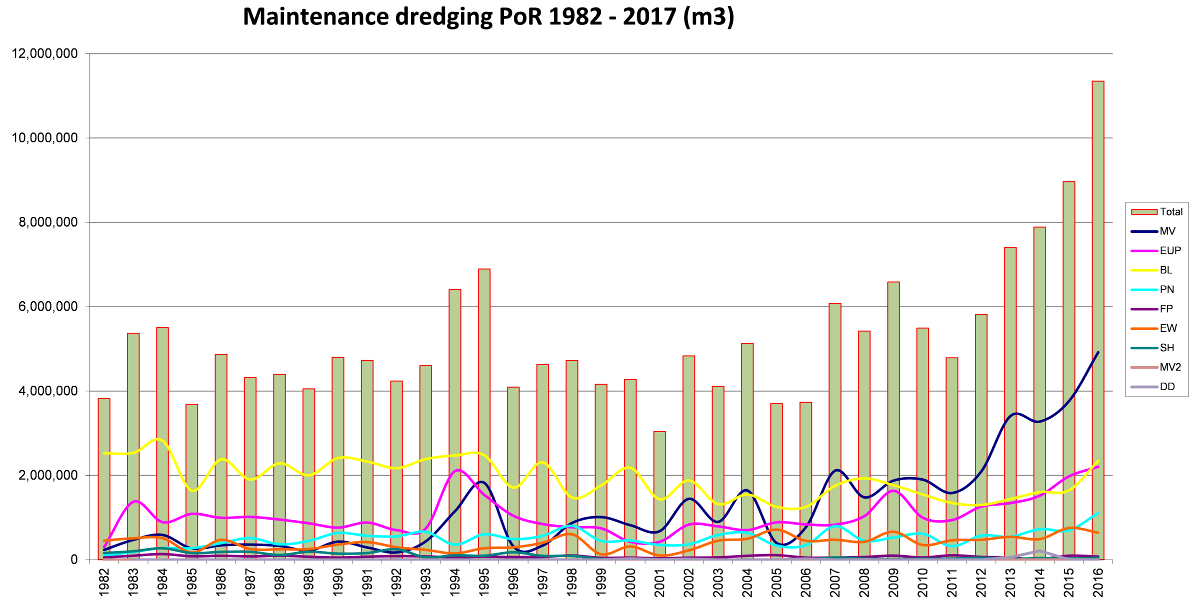

Figure 1.2: Total maintenance dredging volumes of all sections under control of the PoR

1.2. Objective

The objective of this research is to identify the main mechanisms for the increased maintenance dredging volume at PoR over the problem period and to relate this increase to historic events. A second objective is to identify a measure to reduce the maintenance dredging activity. To reach the objectives, the following main research question is introduced:

What is the dominant mechanism leading to the increase in maintenance dredging volumes at the Port of Rotterdam in the last decade and which measure could potentially reduce the maintenance dredging activity in the Maasvlakte-area?

1.3. Research approach

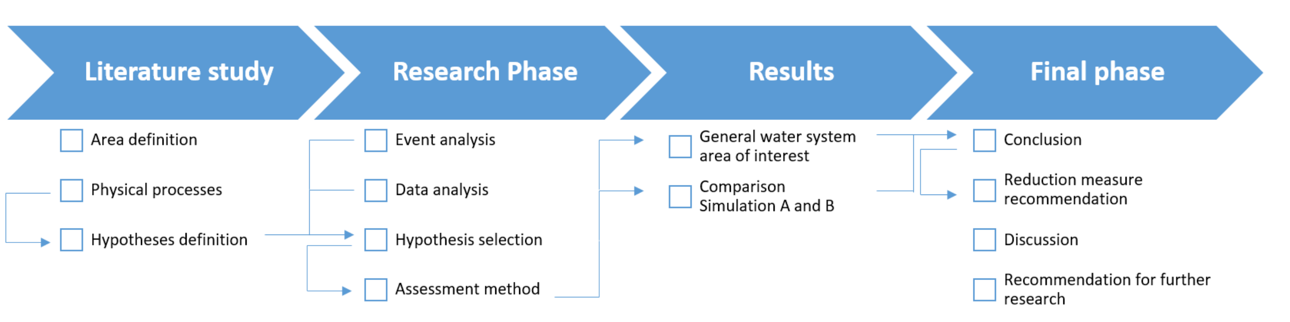

Figure 1.3: Schematisation of the research approach

To reach the objective, the research is divided into four phases: 1) a literature study; 2) the research phase; 3) the presentation of results; 4) the final phase. A schematisation of the research approach is presented in the flow chart of Figure 1.3. A detailed description of the phases is given below. The report is divided into chapters. Each chapter consisting one (part of a) research phase. Each chapter itself is divided into sections, each containing a specific subject of the phase.

1) The research starts with a literature review (Chapter 2). First a description of the area of interest and its

site conditions is given. Subsequently the for this research relevant physical processes, characteristics of the sediment present in the defined area, and typical estuarine sedimentation mechanisms are outlined. By interpreting this background knowledge regarding PoR specifically, the first research phase results in the definition of three hypotheses of factors that potentially induce the problem.

The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in:

1. *Local hydrodynamics by an internal intervention to port layout or geometry;*
2. *External factors, resulting in a change of general hydrodynamics or sediment supply;*
3. *Dredging strategy of the asset managers;*

2) The research phase (Chapter 3) starts with presenting the research analyses. An event analysis is performed to describe all events experienced by PoR since 2005 with a potential noticeable influence on the maintenance dredging volumes. Subsequently a data analysis based on the administrated maintenance dredging volumes of the area of interest is performed. The data analysis starts providing an overview of the maintenance dredging activity over the entire PoR and scales down in five steps to finally focus on the area the problem is concentrated. Based on the data analysis *hypothesis 2.* is rejected as the dominant factor for the increase in maintenance dredging.

The following analysis studies the correlation between the event and data analysis. This results in the selection of *hypothesis 1.* for further assessment that is specified to:

'The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2 with an open connection to MV1'

A last analysis concerns the maintenance dredging strategy. As will become clear later in the report, the maintenance dredging over the area of interest is executed by two parties, PoR and Rijkswaterstaat (RWS). Essential data and information on the strategy of RWS is missing and hence, based on the maintenance dredging strategy analysis, it is decided to leave *hypothesis 3.* untreated for further research.

The last step of the research phase describes the assessment method of *hypothesis 1.*. With use of the hydrodynamic flow model that is part of 'Operationeel Stromingsmodel Rotterdam' (OSR, translation: operational flow model Rotterdam) two model simulations are run. One excluding (Simulation A) and one including the construction of MV2 (Simulation B). The results of both simulations are compared to each other to identify differences of the hydrodynamic conditions due to the specific event.

3) The next phase (Chapter 4) contains the presentation of the results of the hypothesis assessment. First a general description of the water system in the area of interest is given, based on Simulation A. Subsequently the outcome of Simulation B is compared to Simulation A, to identify and discuss the differences observed. The parameters of the simulations that are discussed are tidal discharge, water level, salinity and horizontal flow velocities, as these are the parameters expected to experience the most impact by the studied event.

4) In the final phase (Chapter 6) the conclusions out of the previous phase are drawn. Based on these conclusions the hypothesis is accepted or rejected as the dominant factor responsible for the research definition. Depending on the outcome of the assessment, a suitable recommendation of a potential reduction measure is given. The research closes with identifying and discussing the assumptions done during research and the reliability of the used data. Finally a recommendation for further research is made.

2

Literature review

The outcome of the literature study is presented in this chapter. First a detailed description of the area of interest and its site conditions is given in Section 2.1. Section 2.2 describes the sediment properties and physical processes of cohesive sediments. Some specific harbour and estuarine sedimentation mechanisms are outlined in Section 2.3. The chapter results in the definition of three hypotheses of the potential dominant factor responsible for the increase in maintenance dredging volume experienced by PoR, described in Section 2.4.

2.1. Area definition and hydrodynamic conditions

A description of the area that will be subject to research is given in this Section with an elaboration of the decisions. A description of the maintenance dredging activity in the area is given and details of the main characteristics of the system in the form of fresh water inflow and tide are provided.

The area that is subject to this research is part of the Rhine-Meuse estuary (Figure 2.1) and consists of all harbour basins of the Port of Rotterdam, the Rotterdam Waterway, New Meuse and Old Meuse. The eastern boundaries are set at the Stadhavens. This is done based on the availability of maintenance dredging data in that specific area. The boundary of the estuary itself, where no tidal influence is noticeable, is further upstream. The western boundaries of area that is subject to research are set at Hook of Holland (HoH) and the Haringvliet sluices, as these form the respectively open and closed connections to the North Sea [De Nijs et al., 2011]. The entire area as described above will from here on be referred to as the area of interest.

The maintenance dredging over the area of interest is executed by two parties, Rijkswaterstaat (RWS) and PoR. Roughly it can be stated that RWS takes care of the river and waterways in the area of interest, while the harbour basins are under control of PoR. A plan overview is presented in Figure A.2 of the Appendix. The plan is further treated in Chapter 3. In the harbour basins (controlled by PoR) the dredged material predominantly consists of silt. Material dredged at the Rotterdam Waterway and New Meuse (controlled by RWS) can contain sand, fine sand and silt, depending on the exact location.

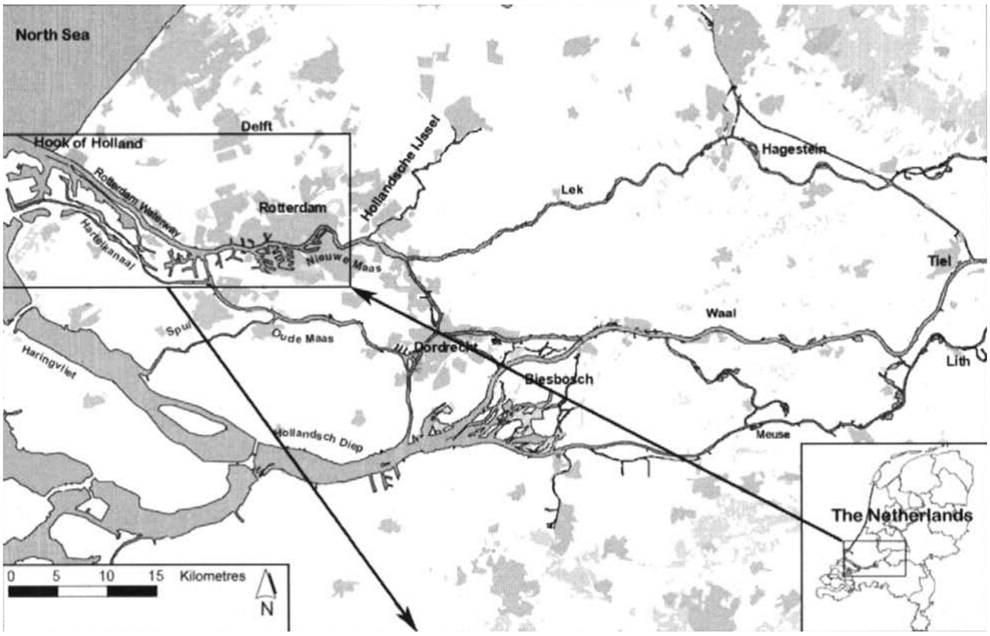

Figure 2.1: The Port of Rotterdam located in the Rhine-Meuse estuary [De Nijs et al., 2008]

Fresh water inflow
Fresh water is supplied to the estuary by the rivers Rhine and Meuse of which the Rhine is responsible for more than 80% of the total discharge. The average summer and winter discharge of the Rhine are approximated at respectively 1800 and 2600 m^3/s [De Wit et al., 2007]. The Haringvliet sluices regulate the fresh water distribution of the Rhine-Meuse delta according to a discharge program. The sluices are closed for Rhine discharges below 1700 m^3/s, transporting all fresh water through the Rotterdam Waterway. Above 1700 m^3/s the sluices are opened during low water at the North Sea to prevent salt intrusion in the Haringvliet.

Tide
The tide measured at HoH is semi diurnal with a marked diurnal inequality and has a mean spring and neap tidal range of approximately 2 and 1.2 metres respectively. The maximum tidal current exceeds 1 m/s. Under typical tidal and fresh water discharge conditions the tip of the salt intrusion reaches the mouth of the Botlek Harbour. [De Nijs et al., 2009]

2.2. Sediment properties and physical processes

A general, purely theoretical description of sediment properties and the physical processes associated with it is presented in this section. By doing so, background knowledge on the fine details of the base of the sedimentation processes is obtained, which in the end is the origin of the problem. The section only includes PoR related theory. The focus is on the physical processes of fine sediments (classified d < 63 μm, Dutch Standards) as these are predominantly present in the water system of the area of interest, and differ from sediments with a larger particle size as for example sand.

Because of the small mean particle size, electrostatic bonds and Van der Waals forces can be formed between particles, resulting in cohesion. Cohesion rates can be enhanced under certain circumstances and depends on the composition of the material and the location it is transported from [Van Kessel, 1998]. A schematic representation of the characteristic cohesive sediment processes is given in 2.2, the relevant processes are briefly treated below.

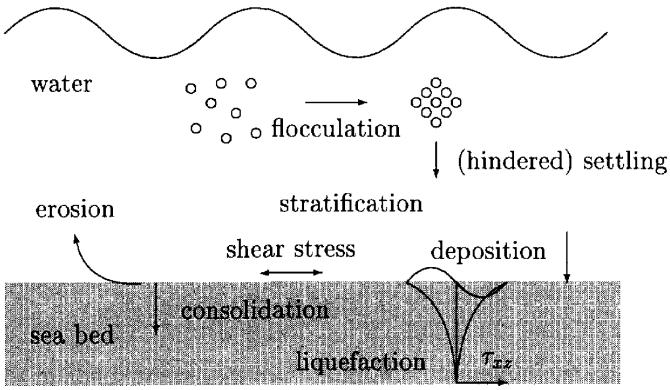

Figure 2.2: Schematic representation of cohesive sediment processes [Van Kessel, 1998]

Cohesive sediment can be present in three manifestations, namely: 1) in suspended, diluted form in the water column, in case of fine sediments called suspended particulate matter (SPM); 2) in aggregated, highly concentrated but still fluid form near the bottom; 3) in solid, consolidated form at the bottom, of which it is part. Suspended particles can collide and tend to aggregate in water. These collisions are mainly governed by Brownian motion, differential settling and turbulent motion. The aggregation process is called flocculation.

Under the influence of gravity, settling occurs as the density of the particles exceeds the density of the water. The settling velocity of a spherical particle can be calculated with the well known Stokes' law:

$$v_s = \frac{(\rho_p - \rho_w) g d_p^2}{18\mu_w} \quad \text{for} \quad (Re \leq 1)$$

- v_s - settling velocity (m/s)
- ρ_p - mass density of the particles (kg/m^3)
- ρ_w - mass density of the water (kg/m^3)
- g - gravitational acceleration (m/s^2)
- d_p^2 - diameter of the floc (m)
- μ_w - dynamic viscosity water $(kg/m * s)$

Floc growth is enhanced by an increase of the SPM concentration, as the collision rate increases. As a result, the settling velocity will increase with the concentration. [Van Kessel, 1998] High SPM concentrations generally occur near the river bed and can cause a high downward volume flux of flocs that has to be compensated by an upward volume flux of water. In case of high SPM settling concentrations, a considerable countercurrent is created, affecting the settling velocity. This phenomenon is called hindered settling. [Winterwerp, 2002].

Once the flocs are deposited, they tend to get more compacted as it is buried by more recent deposits, with as a result that the effective stresses increase. This compaction process is known as consolidation. During consolidation, particles become gradually supported by the grain matrix because of the increase of the effective stress, which is the difference between the total and the water pressure. As a result of the decrease in volume, water is squeezed out of the soil and an increase in yield strength, approximately proportional with the increase of the effective stress, is observed. This process can result in layers with different densities stacked over each other, also known as stratification. The consolidation process ends when the effective pressure equalises the hydrostatic pressure and pore water outflow stops. The resulting strength of the soil can become large enough to withstand eroding forces driven by tides and waves. In that case the sediment becomes a permanent part of the river bed. However, before reaching that point of consolidation the deposition is only temporary and erosion can occur.

Distinction is made between surface erosion, resuspension of singular particles at the river bed, and bulk erosion, which is the failure of a sediment layer. Surface erosion will occur if the bed shear stress, exerted by current or by orbital wave motion, exceeds the critical shear strength for erosion. In case of cohesive sediment the bonding between two particles has to be partly broken before erosion occurs. Therefore the critical shear stress depends on the compaction of the river bed resulting from consolidation. [Van Kessel, 1998]

2.3. Estuarine sedimentation mechanisms

Now a theoretical description of the sediment properties and physical processes on a small scale is provided, this section will further elaborate on the port and estuarine specific sedimentation mechanisms. As described in Section 2.2, fine sediment can be present in the water column in three different forms. This section focuses on the sedimentation processes in the form of SPM.

Transport of SPM is caused by advection and can differ over the water column. The sediment transport profile is the product of the sediment concentration profile and the velocity profile, which is shown in Figure 2.3. A net transport of sediment occurs if the sediment inflow is higher than the sediment outflow. In case of an estuary a complex situation exists as the sediment concentration profile, the velocity profile and hence the sediment transport profile vary over time. In order to understand the siltation patterns in PoR, the variation of the sediment concentration and exchange flows within the tidal cycle needs to be known [Van Maren et al., 2009]. This way factors that might be of influence to the problem can be identified.

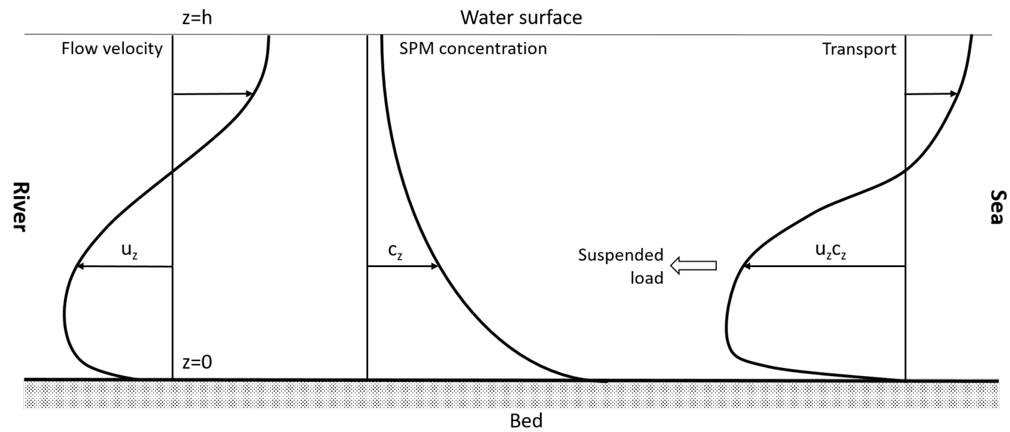

Figure 2.3: Relationship of estuarine suspended sediment transport (vertical axis) to the flow velocity and the suspended sediment concentration steepness, based on [Van Rijn et al., 1993]. The flow velocity profile is typical for estuaries and results of estuarine circulation

The sediment concentration profile depends on the estuarine hydrodynamics and sediment dynamics. The estuarine hydrodynamics and sediment dynamics are mainly formed by the combination of tide, river discharge, salinity distribution, weather conditions, shipping and sediment properties. An inland residual sediment transport is induced by tidal effects of the sea. According to literature this is mainly formed by *tidal flow asymmetry*, *settling lag* and *scour lag* effects, and the effects of *estuarine circulation*. On the other hand, the river generates a residual seaward sediment transport. The various residual sediment transports converge somewhere within the PoR, resulting in high sedimentation rates and the formation of the *estuarine turbidity maximum* (ETM) [De Nijs et al., 2009]. The mechanisms mentioned above are briefly explained below and are of importance in order to understand the sedimentation processes within estuaries.

- *Tidal flow asymmetry* - difference in magnitude and duration between ebb and flood tidal currents, produced by the distortion of the tidal wave propagating on the coastal shelf and entering bays and estuaries. [Dronkers, 1986]

- *Settling lag* - a higher velocity is required to bring a particle in suspension than the velocity necessary for keeping it in suspension [Postma, 1961]
- *Scour lag* - after the current velocity has dropped below the velocity necessary for keeping a suspended particle in suspension, it still takes some time before the particle reaches the bottom. This effect is strongly noticed in case of fines [Postma, 1961]
- *Estuarine circulation* - residual flow pattern in an estuary induced by the density difference between seawater and river water, see Figure 2.3 ([Postma, 1967]. cited by [De Nijs et al., 2010]). This phenomenon is described in more detail in this section under 'density induced currents'
- *ETM* - the zone of highest turbidity in an estuary resulting from sediment fluxes, turbulent resuspension of sediment and flocculation of particulate matter [Schuttelaars and Friderichs, 2003]

The specific process responsible for siltation of harbour basins is the exchange of sediment-rich water of the high energetic river and sea with sediment-poor water of the low energetic harbour basins. Because the harbour basins have a substantial lower energetic level, sediments that were unable to settle outside the basin might be within. Three in port common mechanisms responsible for the exchange of water of the harbour basin and waterway are: horizontal eddies; tidal filling and emptying; density driven flow. These mechanisms are described in more detail below.

Horizontal eddies
In harbour basins a horizontal circulation can be formed by the interaction with the river. Where the river flow separates from the bank at the edge of the basin, a mixing layer is formed. The mixing layer grows by entrainment (horizontal shear flow between water masses of different turbulence). Where the wake hits the opposite side of the basin, a stagnation zone is formed. Entrainment and the stagnation zone induce a large horizontal circulation of the size of the width of the basin. This circulation, in conjunction with the geometry of the basin, can induce secondary and even tertiary circulations. The entrainment and advection cause a water exchange between the river and the harbour basin. Figure 2.4 presents a schematic overview of the mechanism.

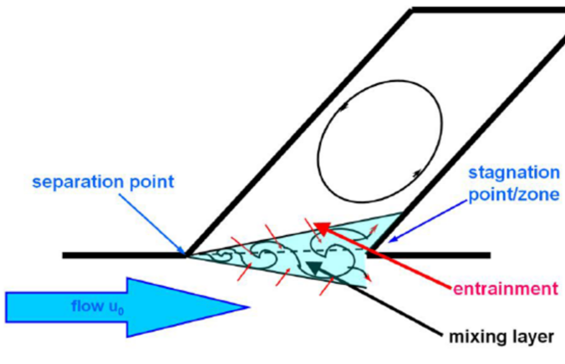

Figure 2.4: Horizontal circulation by flow separation [Winterwerp, 2016]

Tidal filling
In combination with tide, the rate of water exchange between the harbour basin and the river in- and decreases over time. During a tidal filling the mixing layer described above is pushed into the harbour basin by a net inflow of water. Because the shear zone also moves into the basin, the strength of the mixing layer decreases and the exchange of water (and hence sediment) is more dominated by the tidal filling. The opposite occurs during tidal emptying, the wake is pushed out of the harbour basin, and eventually does not induce any exchange between basin and river. [Winterwerp, 2016] Over the entire tidal cycle the net inflow of water is zero, but the net sediment flux might be positive due to settling during tidal slack. Other tidal filling effects on sedimentation are described under the header 'density induced currents' below.

Density induced currents
Density currents are induced by a density gradient in the water as a result of saline and fresh water, water temperature and/or sediment concentration. A gradient can be both vertical and horizontal, affects the flow

structure and hence the sediment transport profile. The effects of both types of density gradients (horizontal and vertical) are briefly discussed below.

In case of an estuary, fresh water from inland meets saline water from the marine environment which, depending on the mixing rate, typically results in a vertical density gradient. Because saline water has a higher density than fresh water, saltwater intrusion (by tidal filling) can occur beneath the fresh water [Schuttelaars and Friderichs, 2003]. During rising flood the salinity of the river is typically higher than the salinity of the harbour basin and a near-bed inflow of saline water into the basin occurs. During ebb the opposite occurs and a near bed outflow of saline water occurs. As the sediment concentration is highest near the bed, this is of significant influence to the sediment transport and hence an of great interest for this research.

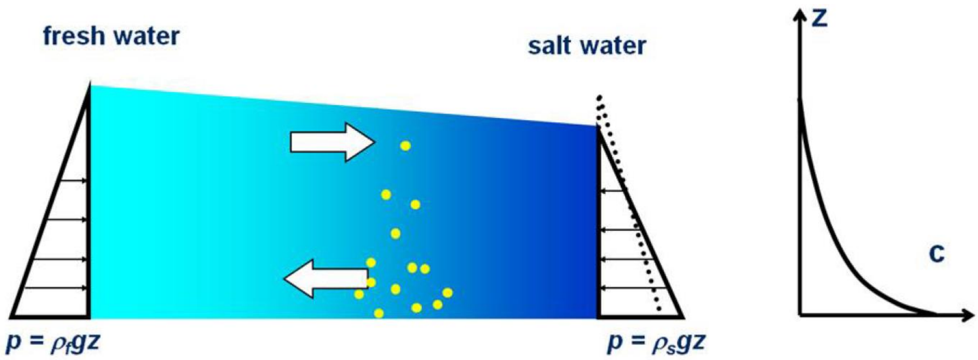

Figure 2.5: Schematic presentation of estuarine circulation induced by a horizontal density gradients. On the right the sediment concentration profile is depicted. (Winterwerp [2016])

Figure 2.5 is used to explain a density current induced by a horizontal gradient. At equilibrium, the total force on the left and right boundary should be identical. The stress distribution follows from the hydrostatic pressure distribution. Hence, the higher hydrostatic pressure near the bed at the saline side should be compensated with a slope in the water level. This induces estuarine circulation, which is described earlier.

On top of the horizontal density gradient is the effect of the tide. Take into account a water body as depicted at the top of Figure 2.6 with only horizontal density gradients and two cases, ebb and flood. During the ebb case, fresh water flows over the saline water at the bottom (depicted in the middle of Figure 2.6). This is a stable situation because the denser water is below the fresh water, imposing stratification. During flood (depicted at bottom of Figure 2.6) the opposite occurs and denser water flows over the fresh water. In this case an unstable situation occurs, resulting in an inreasin of the mixing rates. [Winterwerp, 2016]

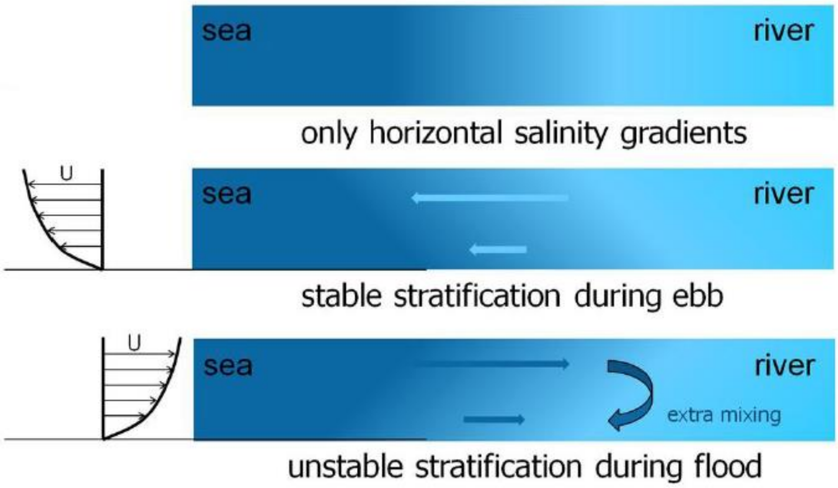

Figure 2.6: Schematic presentation of tidal straining of a water body (top drawing) in case of ebb (middle drawing) and flood (bottom drawing). [Winterwerp, 2016]

2.4. Hypotheses

The aim of the literature review is to provide insight into the theoretical background regarding the research problem. First an overview of the area of interest and its main characteristics is given in Section 2.1. The purely theoretical background of sediment properties and physical processes is outlined in Section 2.2. Together these two sections clarify that the focus of this research has to be at the behaviour of SPM within PoR and provide a theoretical overview of the origin of the research problem. Subsequently the more port and estuarine specific sedimentation mechanisms considering SPM are described in Section 2.3, as these are the processes governing the sedimentation rates within PoR.

No literature is found that specifically describes the factors that are potentially responsible for a change in sedimentation rates within an environments as PoR. For that reason the theory described in this chapter is interpreted regarding PoR and the factors that might lead to an increase in sedimentation rates at PoR over the last decade are identified. The result is the definition of two research hypotheses. In addition the more practical side of the research problem is considered, as the problem originates from the maintenance dredging data provided by PoR instead of sedimentation rates. This results in the definition of a third and last research hypothesis.

The reasoning for the first two hypotheses is based on the sediment transport profile described in Section 2.3 and schematised with Figure 2.3. A change in sedimentation rates is logically the result of a change of the sediment transport profile over the tidal cycle. As the sediment transport profile is the product of the flow velocity profile and the sediment concentration profile, a change of one of both will result in a change of the sediment transport.

1) Examples are given regarding port and estuarine specific sedimentation mechanisms. Section 2.3 clarifies that water exchange mechanisms between the river and harbour basins are governing the sedimentation rates. These water exchanges are strongly determined by the layout and geometry of the port in combination with the environment in front of the basin, which is logically formed by the external factors. Regarding PoR, several internal changes to the port layout and geometry took place over the last decade, examples are the construction of a new terminal or the deepening of the New Waterway. These interventions logically have its impacts on the flow velocity profile within the port and hence affect the sediment transport profile over the tidal cycle. The first hypothesis is based on changes of this form and is defined as: *The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in*:

1. *Local hydrodynamics by an internal intervention to port layout or geometry*

2) It is clarified by Section 2.3, that the sediment concentration profile is mainly formed by the external factors. The most important external factors of impact to the hydrodynamic conditions in the area of interest are tide and river discharge. Next to the determinant role regarding the hydrodynamic conditions, both environment are also responsible for the sediment supply to the system. The hydrodynamic conditions in combination with the sediment present in the system form the sediment concentration profile. A deviation of the external factors hence is expected to result in a significant change to the sediment transport profile. The influence of external factors to the sedimentation rates within PoR is covered by the second hypothesis of this research, defined as:

1. *External factors, resulting in a change of general hydrodynamics or sediment supply*

3) As mentioned, the third hypothesis does not result from the literature review and is of a more practical origin. As described in section 1.1, the problem of PoR is identified based on the administrated maintenance dredging volumes, which will be treated in more detail in Chapter 3. It must be clear that these volumes do not directly correspond to sedimentation rates, but are influenced by the maintenance dredging approach of the asset manager and so by changes to it. A different approach of the maintenance dredging activity will have its impact on the volumes administrated by the asset manager. Hence changes with a strategical origin of the maintenance dredging activity are captured within the last hypothesis for this research:

1. *Dredging strategy by the asset manager*

A last important factor that can not be left unmentioned results from Section 2.2, which describes the physical processes of fine sediments. It becomes clear that the characteristics of the sediment determines its physical behaviour and hence the sediment concentration profile. This means that a change of sediment properties within the system can result in a change of sedimentation rates. Regarding this research a change of the composition and therewith the sediment properties of the material present in the system, might be a potential factor leading to the increase in maintenance dredging volume. A reasoning like this results in the definition of a hypothesis in the form of: '4. *A change in sediment properties*'. However, no indications that could result in a change of sediment properties within the area of interest are found and a deeper study to that subject is not within the research scope. For that reason the hypothesis is assessed to be unlikely and not included for further research.

The literature review described in this chapter led to the definition of three hypotheses. In the following chapter the research analyses are performed to further study the background of the problem. Based on the outcome of the analyses a selection of one of the above defined hypotheses that will be subject to a hypothesis assessment is done.

3 Research

In Chapter 2 three hypotheses are defined that describe the factors potentially leading to the increase in maintenance dredging volume at PoR based on a literary background. This chapter describes and presents the steps taken for research. First the research analyses provide insight into the background of the problem experienced by PoR are presented in Section 3.1. Based on the outcome of the results of the research analyses, one hypotheses that will be subject to a hypothesis assessment is selected in Section 3.2. The method and details of the hypothesis assessment are outlined in the last section of the chapter, Section 3.3.

3.1. Research analyses

To obtain more insight into the background of the problem, several research analyses are performed. An event analysis (Section 3.1.1) is done to outline all events with a potential influence on the sedimentation rates experienced by PoR over the last decade.

Subsequently a thorough data analysis (Section 3.1.2) of the administrated maintenance dredging volumes of the last decade over the area of interest is performed to provide an overview of the development of the maintenance dredging volumes. The data analysis starts taking into account the entire PoR and scales down in several steps to the area the problem is concentrated, to further elaborate on this specific area.

With use of the outcome of the event and data analysis, a study to the correlation of the experienced events and the increase in maintenance dredging volume is performed. The correlation analysis (Section 3.1.3) is in particular done to study the relation of *hypotheses 1.* and *2.* The last step presented in this section is the maintenance dredging strategy analysis (Section 3.1.4), that is discussed regarding *hypothesis 3.*

3.1.1. Event analysis

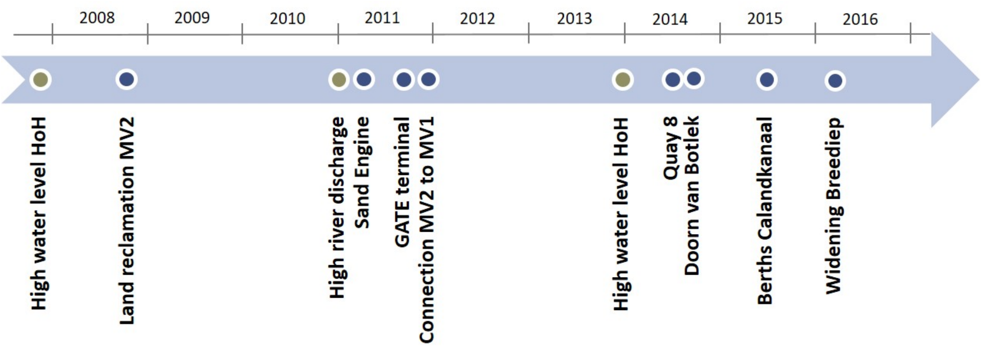

Figure 3.1: Timeline of internal (blue dots) and external events (green dots) with a potential influence on the maintenance dredging volumes of PoR

The aim of the event analysis is to point out all events experienced by PoR with a potential noticeable influence on the total maintenance dredging volumes since 2005. Earlier events are expected to be noticed in the data before the problem period. To assign the events to the hypothesis it is related to, distinction is made between internal events (regarding *hypothesis 1.*) and external events (regarding *hypothesis 2.*), which are respectively human influenced and nature driven.

Internal events

Internal events are human influenced interventions to PoR, the upstream rivers or the adjacent coastline. Examples are adjustments to port layout or geometry. Only the events assessed to be potentially noticeable in the maintenance dredging volumes are taken into account for this research. The events are outlined below. The locations are shown in Figure 3.2. A description of each of the events is found in Appendix B.

- *2008* - Start land reclamation for construction of Maasvlakte 2 (A)
- *2011* - Construction Sand Engine pilot project (B)
- *2011* - Construction GATE terminal (C)
- *2011* - Connection of Maasvlakte 2 to Maasvlakte 1 (D)
- *2014* - Construction quay 8 (E)
- *2014* - Removal of 'Doorn van Botlek' (translated: Thorn of Botlek) (F)
- *2015* - Deepening berths Calandkanaal (G)
- *2016* - Widening of Breeddiep (H)

Figure 3.2: Map of the internal events taken into account for research

External events

External events are the events experienced by PoR that are nature driven. Examples are deviating weather and climate conditions. The port is subject to influences of both the river and marine environment. For this research only the most extreme conditions of both environments responsible for a residual sediment flux occurred since 2005 are taken into account. The average conditions are described in Section 2.1. In the case of the river environment the highest discharge measured at Lobith is taken into account. A high river discharge is typically associated with a high seaward sediment flux. Regarding the marine environment the two highest water levels measured at HoH since 2005 are taken into account. A high water level results from an increase to the tidal cycle amplitude, which is the driving force responsible for residual landward sediment fluxes. Additionally a high water level (generally caused by wind setup due to stormy weather) of the North Sea is typically associated high energetic conditions, which stirs up the sediments and results in a high sediment concentration in front of the port. Details of the considered external events are shown in Table 3.1.

Event	characteristic	date
High water level HoH	316 cm 301 cm	09 November 2007 06 December 2013
High discharge Rhine (Lobith)	8315 m^3/s	17 January 2011

Table 3.1: Details of external events taken into account for research

All events taken into account are summarised and plotted on the timeline in Figure 3.1. The outcome of the event analysis will be used in Section 3.1.3 to study a correlation with the research problem.

3.1.2. Maintenance dredging volume data analysis

PoR is aware of the problem described in Section 1.1 by an increase of the administrated maintenance dredging volumes. An analysis of the data is performed to provide a better understanding of the actual problem and more insight into the development of the maintenance dredging activity in PoR over in particular the last decade. The details of the data analysis are presented with graphs, summarised in Appendix C. However, all main figures are also presented in this section below the subject it is related to. The analysis is divided into five main steps. Step *1.* and *2.* approach PoR as one entire system to perform analyses of the maintenance dredging volume development on macro-scale, both from a different point of view. Subsequently in step *3.*, *4.* and step *5.* PoR is taken into account in more detail, on base of harbour basin and so-called dredging section (explained later on). This approach is applied to scale down and focus on the area(s) the problem is located resulting from the first two steps. Closing a thorough analysis of the maintenance dredging development over the problem area is performed. The steps together with a brief explanation are outlined below:

1. **Seasonal trend** - A study to potential changes of the seasonal behaviour of the yearly maintenance dredging activity;
2. **North Sea influence** - Comparison of PoR as one entire system to the comparable (small scale) Port of IJmuiden;
3. **PoR overview** - Provides an overview of the the maintenance dredging activity and development on base of harbour basin to locate the problem area(s);
4. **Water systems** - Compares the two water systems resulting from step 3) on long-term trend;
5. **MV-area** - Elaborates on the internal maintenance dredging development of the water system the problem area is located on dredging sections base;

The data analysis is based on the maintenance dredging volumes administrated by PoR and RWS. Both use so-called dredging sections to administrate the dredged volumes. Each harbour basin and waterway is split up into several dredging sections. An overview of all dredging sections is provided in Figure A.2 of the Appendix. The figure also describes which asset manager is responsible for the sections. For each dredging section the maintenance dredging volumes are registered, in case of PoR in cubic metres, or in case of RWS in tons dry solids (tds). All values mentioned in this report will concern cubic metres unless stated otherwise. The conversion factor of tds to cubic metres depends on the composition of the material and differs per area. All necessary conversion factors are provided by RWS and inaccuracies due to conversion are assumed to be negligible. The three data-sets that are made available for this research are:

a) yearly dredged volumes of all dredging sections under control of PoR since 1981;

b) yearly dredged volumes of all dredging sections under control of the RWS (inclusive the Port of IJmuiden) since 1999;

c) monthly dredged volumes per harbour basin (a collection of multiple dredging sections) since 1999. The location of the named harbour basins is shown in Figure 3.6.

As explained in Section 2.2, silt present at the bottom can be stratified caused by different densities of layers. It is assumed by PoR that for certain relative low densities a silt layer is still navigable. To determine the navigable depth the hard bottom is set at a density of 1.2 $tons/m^3$. Currently research is done to the accuracy of this standard and to the influence of other rheological properties of the sediment. An example is the research done by Kiricheck [2016]. For this research the standards of PoR are adopted and it is assumed that all dredged material has a density of at least 1.2 $tons/m^3$.

The composition of the dredged material differs per section and hence as explained in Section 2.2 also the characteristics and behaviour of the material differ. For this research it is assumed that over the entire area of interest the bed material is similar and contains predominantly mud. This is a reasonable assumption for all harbour basins. The dredged material of the sections under control of RWS (river and waterways) might contain coarser particles (fine sand/sand), which should be kept in mind.

A final comment is made regarding the data used. It is important to be aware that the mentioned volumes do not directly correspond to sedimentation rates, but are administrated dredging volumes which might be influenced by maintenance dredging strategies.

1. Seasonal trend
With use of database *c)* the seasonal trend of the maintenance dredging activity is studied. The trends observed over the base (2005-2012) and problem period (2013-2016) are compared to each other and studied on deviating outcomes. Generally it can be said that the yearly maintenance dredging activity is concentrated over the months February to June. For that reason the use of cumulative yearly volumes over a calendar year (January to December), which is used for data administration by both operating parties, is assumed to be a good approach of the yearly dredging rates and adopted for this research.

The average monthly maintenance dredging volume of all dredging sections under control of PoR plotted in the graph of Figure 3.3, making distinction between the base and problem period. Logically the problem period graph is showing significant higher values, but by comparing both, no clear change of trend over the months is observed. A note should be made regarding the peak observed in September of the graph of the base period. This outlying value is attributed to a deviating amount of maintenance dredging volume (over 1 million m^3) in September 2009. This might be the result of the land reclamation for MV2 starting in 2009, which will be treated later on, and hence does not return periodically.

Regarding the monthly maintenance dredging activity it is assumed that no change of the monthly distribution has occurred over the problem period compared to the base period. From here on the research will only make use of yearly cumulative maintenance dredging volumes (calculated from January to December).

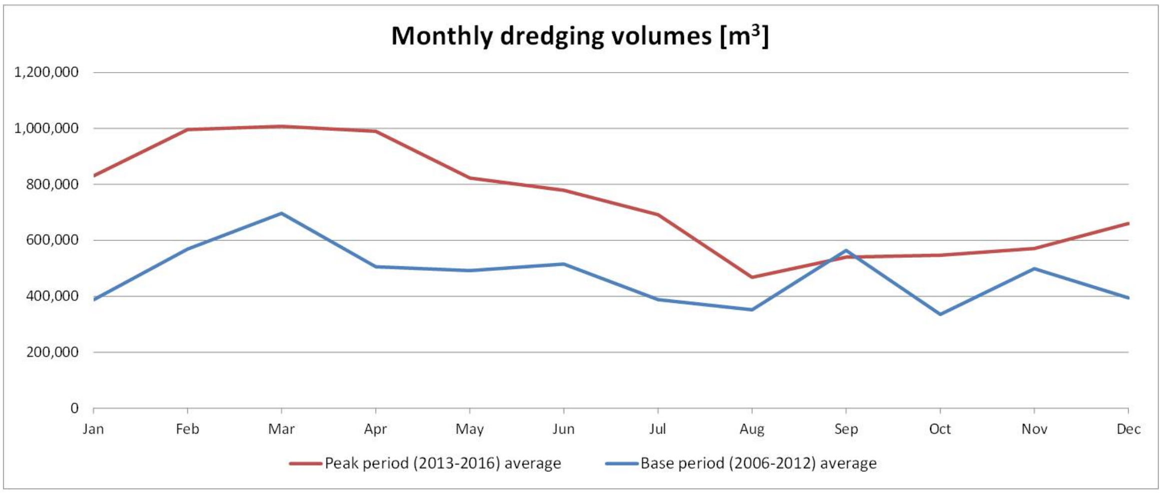

Figure 3.3: Monthly maintenance dredging volumes of dredging sections under control of the PoR. Note is made that in this case 2006-2012 is taken into account as the problem period (instead of 2005-2012) due to the absence of monthly data on some harbour basins in 2005

2. Macro-scale North Sea influence (IJmuiden)
A change of the North Sea conditions might potentially be the driving mechanism for the increase in maintenance dredging volumes at PoR. For that reason it is interesting to compare the maintenance dredging data of PoR with the data of Port of IJmuiden. Port of IJmuiden is relative to PoR a small scale port. It is also located at the west coast of The Netherlands on a distance of approximately 65 kilometres to PoR, contains an open connection to the North Sea and has an hinterland connection with the North Sea Canal. The maintenance dredging in Port of IJmuiden is fully under control of RWS and hence the data is included in database *b)*.

In Figure 3.4 the maintenance dredging volumes of the dredging sections within Port of Ijmuiden are plotted. At none of the dredging sections an increase is observed over the problem period and significant low maintenance dredging volumes are administrated compared to the decade before. It is clear that no similarities of the maintenance dredging development of Port of IJmuiden and PoR are found. Even though Port of IJmuiden is a different system on its own where several other sedimentation processes might be of influence to the sedimentation rates the comparison is valuable. The observation of a similar phenomenon (an increase in maintenance dredging volume over the problem period) would have suggested the macro-scale North Sea environment as an important driving factor of the problem. This is not the case. A more detailed analysis to the relation of external factors and the research problem is performed in Section 3.1.3 of this report.

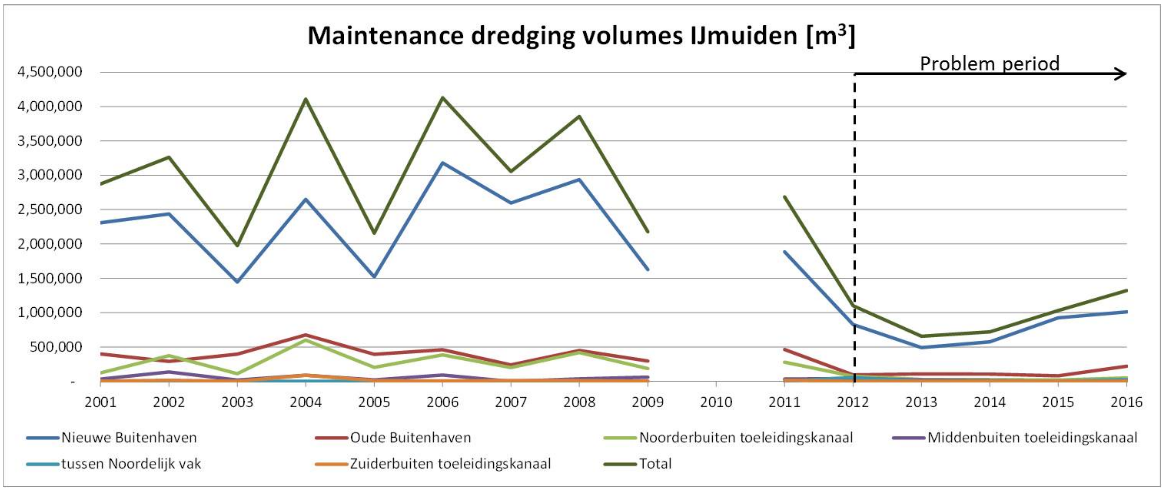

Figure 3.4: Maintenance dredging volumes of the dredging sections within Port of IJmuiden (no data on 2010 is provided)

3. Area of interest overview

With use of database *a)* and *b)* an overview of the maintenance dredging activity over the entire PoR is provided on harbour basin base to locate the area(s) responsible for the increase in maintenance dredging volumes. Figure A.3 and A.4 of Appendix A form the basis of this step of the data analysis. Further insight into the details of both maps is provided with use of graphs below the section it is related to. A summary of the results is given with use of Table 3.2.

Figure A.3 presents a plan of the average maintenance dredging activity, in metres a year over the problem period, for each dredging section. The values are obtained by dividing the average yearly maintenance dredging volume over the dredging section surface. This way the the factor dredging section size (a large dredging section logically results in a higher maintenance dredging volume) is excluded. By doing so a first impression of the areas that are subject to more frequent dredging and where logically the sedimentation rates are relatively high is provided. The results classified in three ranges, details are found in the legend included in the figure.

Because not the (large volume of) maintenance dredging itself is considered as the problem of this research, but the increase to it is, Figure A.4 is introduced. The figure presents an overview of the development of the maintenance dredging activity over the problem period relative to the base period, from here on referred to as problem:base ratio. The problem:base ratio can be calculated by dividing the average yearly maintenance dredging of the problem period over the average yearly maintenance dredging of the base period as shown in the formula below (resulting in a dimensionless parameter). The map is composed as follows. The sections with none to very little influence on the maintenance dredging activity (average <0.05 m/y over the problem period, depicted as green sections in Figure A.3) are left out to focus on the dredging sections that are of interest regarding the problem. An additional analysis of the sections that are left out is done to make sure no remarkable occurrences are overlooked. Subsequently the problem:base ratios of the remaining dredging sections are classified in three ranges. A section subject to a decrease of the maintenance dredging activity over the problem period compared to the base period is depicted as a green surface (problem:base ratio below 1). A section represents a slight to substantial increase depicted as yellow (problem:base ratio between 1 and 2). A sections represents a strong increase if it is depicted as red (problem:base ratio above 2). The results including the legend are presented in Figure A.4.

$$Problem : base\ ratio = \frac{Average\ yearly\ volume\ problem\ period}{Average\ yearly\ volume\ base\ period}$$

With use of Figure A.4 two areas with several dredging sections that are of interest (coloured sections) adjacent to each other become clear as shown in Figure 3.5. Both areas can be seen as a specific water system on its own, where the dredging sections are related to each other and cover an area where the maintenance dredging activity of PoR is concentrated. The water systems are named CaBe-system (Caland- Beerkanaal system) and RoWa-system (Rotterdam Waterway system) and will be subject to further analysis in the next step of the data analysis, but are already treated here because they are referred to at some parts of the macro-scale analysis.

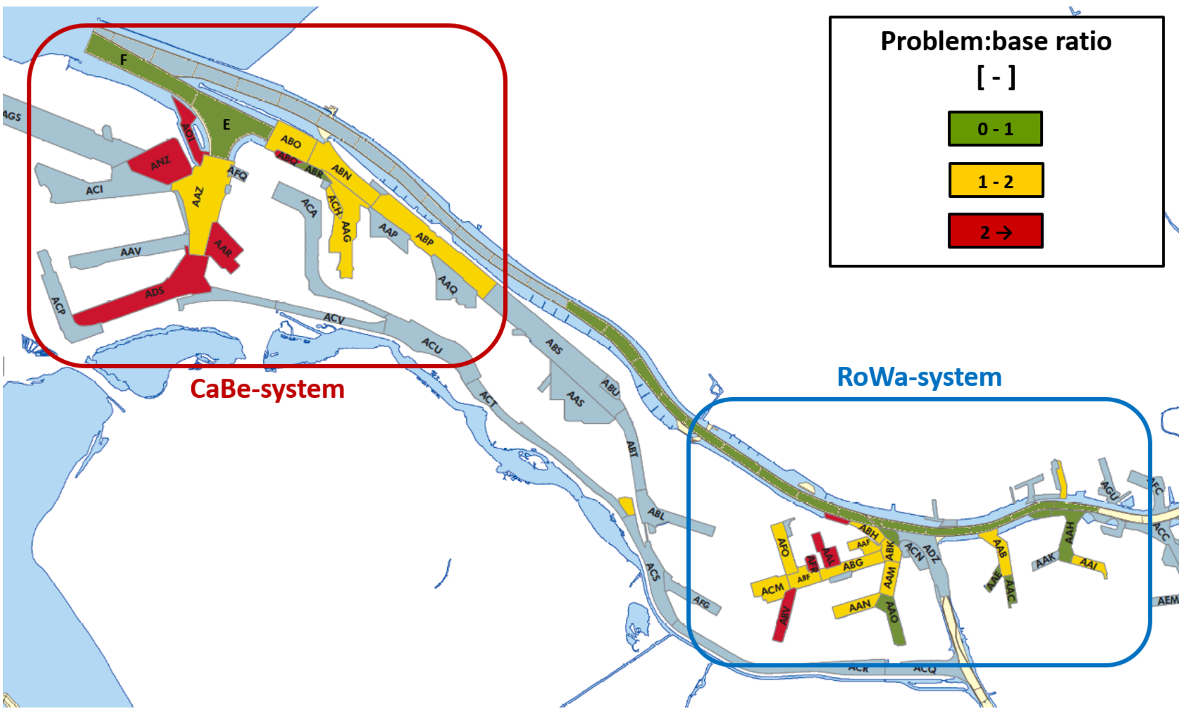

Figure 3.5: Location of Cabe-system and RoWa-system within PoR

The analysis of the area of interest results in three assumptions that are of great importance for further research. The assumptions are classified with **A), B)** and **C)**, and outlined below. Subsequently each assumption is elaborated in more detail.

A) MV1 is the main contributor responsible for the increase in maintenance dredging volume observed over the problem period by PoR. MV1 is part of CaBe-system;

B) Considering all dredging sections within the area of interest (under control of both PoR and RWS) no significant increase of the total maintenance dredging volume over the problem period is observed. A deviating high volume, but within the bandwidth of the last decade is noticed in 2016. Which implies a shift of location of the sedimentation rates instead of an increase over the entire port area;

C) The sections responsible for a decrease in total maintenance dredging volume over the problem period observed by RWS are located in front of and adjacent to MV1. These sections are part of CaBe-system.;

A) Additional to the plans of Appendix A an analysis of the maintenance dredging data of the harbour basins (Figure 3.6) under control of PoR is performed. The results are summarised within Table 3.2. More details behind the data analysis are presented with use of the graphs in Appendix C. A brief description of each basin is given below.

Harbour basin	Problem period average total volume	Dredging area surface 2017	Problem period average dredging per square metre	Problem:base ratio
	$[mln\ m^3/y]$	$[mln\ m^2]$	$[m/y]$	[-]
MV1	3.8	11.6	0.33	2.52
MV2	0.0	3.7	0	0
EUP	1.8	16.0	0.11	1.67
BL	1.8	6.1	0.29	1.16
PN	0.8	1.4	0.53	1.55
FH	0.1	0.7	0.08	0.78
EW	0.6	5.4	0.11	1.21
SH	0.0	1.6	0.02	1.31
Total	**8.9**	**46.5**	**0.19**	**1.7**

Table 3.2: Summary results macro-scale data analysis on harbour basin base

- **MV1** - MV1 is the harbour basin with the second largest surface, has a substantial high maintenance dredging activity per square metre and a problem:base ratio significantly higher than any other harbour basin (factor of 2.52). By comparing these values with the values of the other harbour basins, MV1 is indicated as the main contributor responsible for the increase in maintenance dredging volume within PoR. This assumption is in accordance with the first trend presented in Figure 1.2 of Chapter 1. MV1 is largely part of CaBe-system.
- **MV2** - MV2 is a recently opened harbour basin (see Section 3.1.1), logically no historical data of this basin is available. No maintenance dredging is executed yet at this harbour basin and hence the dredging sections of MV2 are not contributing to the increase in maintenance dredging volume. Even though, MV2 is interesting for further research as it is adjacent to MV1 where the strongest increase in maintenance dredging volumes is noticed;
- **Europoort (EUP)** - EUP is the harbour basin with the largest surface. For that reason the total maintenance dredging volume is substantial. However, the maintenance dredging activity per square metre is relatively low. Considering the problem:base ratio of 1.67, EUP is a contributor to the increase in maintenance dredging volume. Taking into account the plan overview of Figure 3.5, it is noticed the sections that are responsible for the increase are in the same area as the above described main contributor MV1. For that reason EUP is interesting with regards to further research. Several sections of EUP are part of CaBe-system.
- **Botlek (BL)** - BL has the third largest harbour basin surface of PoR and has a relative high value of maintenance dredging per square activity metre. Almost the entire basin is part of RoWa-system (Figure 3.5) and hence, in combination with its high maintenance dredging activity, is considered as the dominant harbour basin in this water system. For that reason BL is of interest for the next step of the data analysis. BL is largely part of RoWa-system;

- **Pernis (PN)** - Remarkably PN has the highest maintenance dredging per square metre of all harbour basins. However, this outcome can almost entirely be described to the contribution of a so-called sediment trap[1] in front of the basin. Additionally PN has a significant high problem:base ratio (1.55), but is hardly noticeable in the total dredging volumes of PoR because of its small harbour basin surface. Even though, PN is part of RoWa-system and some dredging section are of interest for the next step of the data analysis;

- **Fruithavens (FH)** - Based on the combination of harbour basin surface, maintenance dredging per square metre and peak:base ratio, FH is considered not be of contribution to the macro-scale increase in dredging volume. FH is of negligible size and no clear similarities with the macro-scale trend of the maintenance dredging volume are observed;

- **Eem- Waalhaven (EW)** - EW is a harbour basins of average size. Based on its problem:base ratio of 1.21 it is clear that EW follows the trend of the problem period, but is with a relatively low average maintenance dredging per square metre negligible. Also EW is located further landward and is less influenced by the marine environment in contrast to the main contributor, MV1. Additionally, no dredging volume data of adjacent New Meuse in front of the harbour basin is available due to the absence of information of maintenance dredging volumes of RWS (further details are found in Appendix A). For those reasons EW is not further treated in the following steps of the data analysis;

- **Stadhavens (SH)** - SH is the a harbour basin of negligible size, located in the city further upstream. Even though SH has a slightly positive problem:base ratio, SH is considered not be of significant contribution to the macro-scale increase in dredging volume due to the combination of dredging sections surface and maintenance dredging per square metre;

Summarising, MV1 is the harbour basin responsible for the problem as experienced by PoR. At EUP, close to MV1, also a significant contribution to the increase in maintenance dredging volume is observed. A relation between both seems likely and has to be studied in more detail. Next to those harbour basins, BL and PN are of interest for further research due to the development of its maintenance dredging activity. The other harbour basins mentioned are by its maintenance dredging volume relative to the global-trend assessed negligible and excluded for the next steps of the data analysis.

A final note should be made with reference to the two water systems (CaBe-system an RoWa-system) introduced above. It is clear and should be noted that the harbour basins of interest are part of one of these water systems. MV1 and EUP of CaBe-system, BL and PN of RoWa-system (see Figure 3.5). It is important to keep this in mind as it will come back in later in this step of the research analysis.

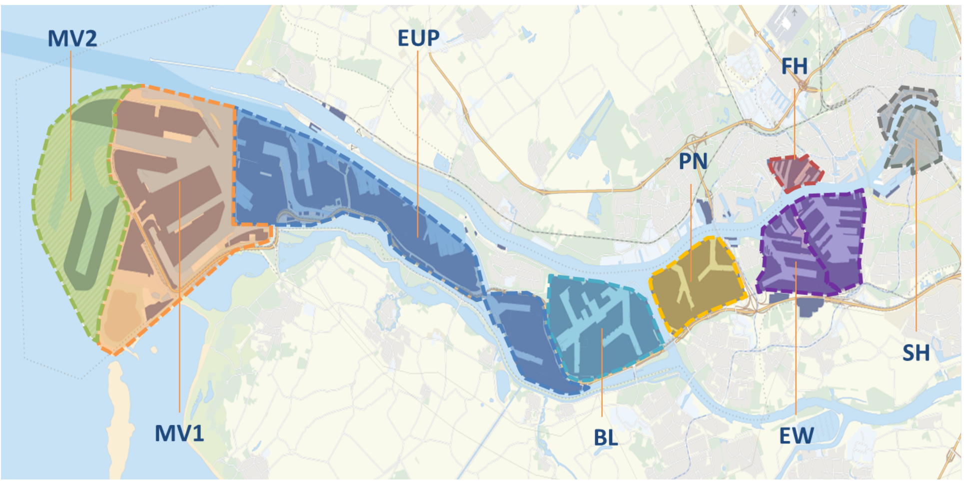

Figure 3.6: Overview of harbour basins Maasvlakte II (MV2), Maasvlakte I (MV1), Europoort (EUP), Botlek (BL), Pernis (PN), Eem- Waalhaven (EW), Fruithavens (FH), Stadhavens (SH)

[1]A sediment trap is a local deepening of the bed level of the harbour basin with the intention to induce sedimentation at that location, as it is more profitable to execute maintenance dredging at that location than further into the harbour

B) By combining databases *a)* and *b)* an interesting finding is discovered, which is presented in Figure 3.7. By adding the dredging volumes of PoR (blue line) and RWS (red line) the total maintenance dredging volume over the entire port area is found (green line), which shows some remarkable results. Where the total maintenance dredging volume of dredging sections under control of PoR is subject to an increase over the problem period, the opposite applies to the dredging sections under control of RWS. Since 2007 a decrease over the sections of RWS is observed, which reaches below the base periods bandwidth (lowest volume over the last decades of approximately 4.5 million m^3 a year) and keeps within this range since 2011.

Looking at the graph presenting the merged total maintenance dredging volume of PoR and RWS, no occurrence of a 2013-2016 problem period is recognizable. The graph presenting the total maintenance dredging volume over the entire port area is strongly fluctuates over the last decades and no clear change of trend is observed (Figure 3.7. For that reason it is assumed that, taking into account all dredging sections within the area of interest, no significant increase in maintenance dredging volumes over the entire PoR takes place over the problem period. A relative high maintenance dredging volume is administrated in 2016, but within the bandwidth of the last decades. This finding is of major interest for this research, as it implies a shift of the location of the sedimentation rates from sections under control of RWS to sections under control of PoR, instead of an increase of the sedimentation rates over the entire port area.

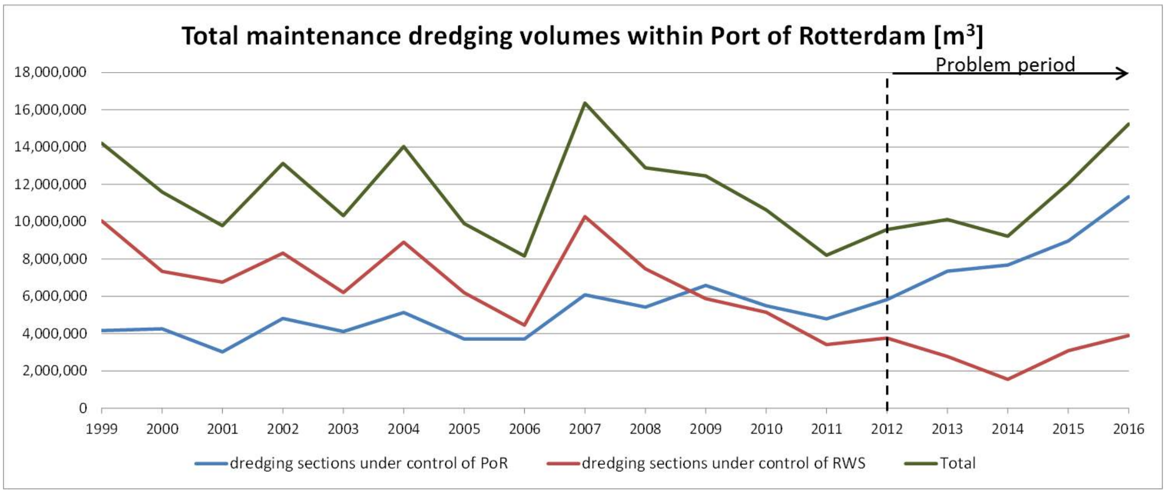

Figure 3.7: Total maintenance dredging volumes within Rotterdam of both asset managers, PoR and RWS

C) Now it is clear that the increase in maintenance dredging volume over the sections of PoR is related to a decrease at the sections of RWS, a following step is to study the location where the decrease is concentrated. It is found that the decrease is not equally distributed over all sections under control of RWS. Details of the maintenance dredging volumes of the RWS sections are presented with use of the graph plotted in Figure 3.8 in combination with the plan of Figure A.3. Based on these figures, it is clear that the dredging sections responsible for the decrease of maintenance dredging volumes by RWS are the section E and F (details on the exact location shown in Appendix A). This is an interesting outcome as the location of these sections is adjacent to MV1, the main contributor to the increase in maintenance dredging volume experienced by PoR (assumption A), and part of CaBe-system. For that reason this finding is subject to a more detailed study in step 5) of the data analysis.

Another area responsible for a (considerably smaller) part of the decrease is the Rotterdam Waterway in front of BL and PN and part of RoWa-system. Both areas are part of one of the systems described in the beginning of this step. Summing the findings done so far by the data analysis up, a relation between the behaviour of CaBe-system and RoWa-system is repeatedly suggested. Subsequently this relation is subject to a further study in the next step.

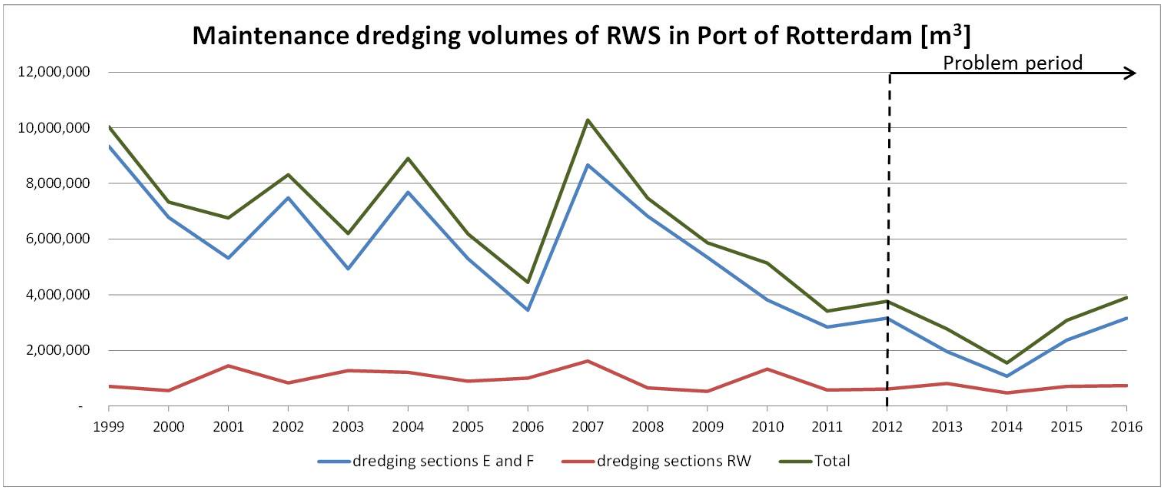

Figure 3.8: Maintenance dredging activity of RWS in Rotterdam, the location of the sections can be found in the Appendices, Figure A.2

4. Water systems

The water systems introduced in step **3)** of the data analysis are subject to an analysis that compares both to each other to study if a similar trend is occurring. The total maintenance dredging volume of both systems is plotted in Figure 3.9. It is noticed that CaBe-system has significant high maintenance dredging volume compared to RoWa-system. A last graph 'others' is added, including all dredging sections except the ones covered by one of the water systems. This is done only to demonstrate the relative small order of magnitude of the other dredging sections compared to the water systems, which justifies that both water systems are indeed dominating the maintenance dredging activity within PoR.

While the total maintenance dredging volumes of both systems differ significantly, the shape of both graphs seems to show several similarities. To find out if both water systems 'act' (follow the same trend, but on a different scale) similar, ratio lines are introduced. A ratio line is a dimensionless line that describes the dredging activity from a system/area/section during the years relative to its base period average, and can be simply calculated with the formula:

$$Ratio = \frac{Total\ volume\ [m^3/y]}{Average\ total\ volume\ base\ period\ [m^3/y]}$$

Both ratio lines are plotted in the same graph presented in Figure 3.10. Even though both water systems are not adjacent to each other and are located at other areas within PoR, their trends indeed seem to show some strong similarities over the last decades. As we know, both water systems are part of the Rhine-Meuse estuary, where the general hydrodynamic conditions on large-scale are formed by external factors as describe in Section 2.3. An influence of these external factors mainly in the form of tide and river discharge is expected to be visible in both systems. The ratio lines form a substantiation of this theory. It is assumed that both water systems follow a similar large-scale trend formed by the external factors.

However, the problem as experienced by PoR is assigned to an increase in maintenance dredging volumes of MV1. The step **3)** of the data analysis describes a relation with the decrease of the maintenance dredging volume of the sections under control of RWS in front of MV1. Both main contributing areas are part of CaBe-system. Hence an analysis to the internal behaviour of RoWa-system is of interest and to study if both systems also internal act similar over the problem period. With use of the Figure C.7 in combination with Figure C.8 shown in the Appendix it is clear that no comparable shift of sedimentation rates is observed at the RoWa-system. This suggests that the external factors are not the dominant mechanism driving the increase in maintenance dredging volumes at PoR as this would have been noticeable in both systems. Looking at the internal behaviour of RoWa-system (Graph C.8, none of the areas show an increase in the same order of magnitude as MV1. The same can be said for the decrease in the sections under control of RWS. CaBe-system itself is from here on seen and referred to as the problem area. Therefore the last step of the data analysis will fully focus on CaBe-system.

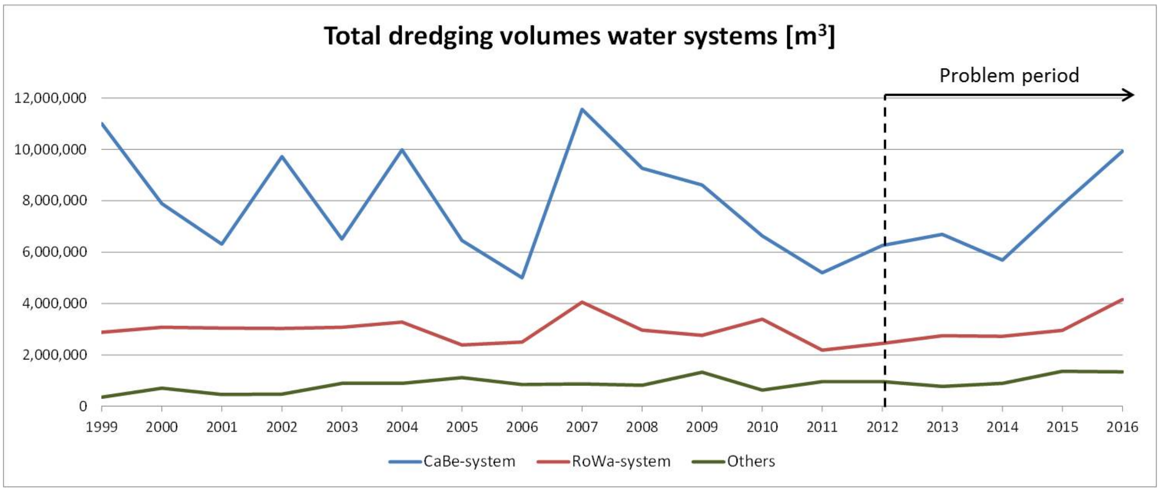

Figure 3.9: Total maintenance dredging volumes of both water systems, CaBe-system and RoWa-system

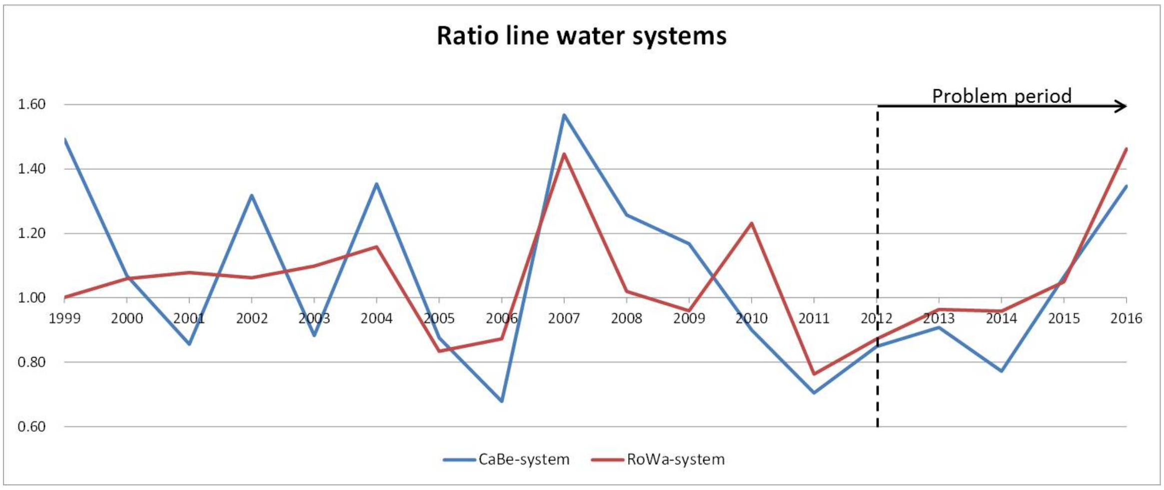

Figure 3.10: Ratio lines of both CaBe and RoWa system, see graphs presented in C for further details

5. CaBe-system

For more details of the actual situation of the problem area, this step fully focuses on CaBe-system, covering both areas of interest resulting from step 3) (MV1, EUP and the sections of RWS in adjacent to both, respectively responsible for a significant increase and decrease of maintenance dredging volumes). To do so the sections of CaBe-system are divided into three areas, the result is shown in Figure 3.11. The plan is composed based on the classification of each dredging section in Figure A.4 (representing the dredging ratios). All dredging sections adjacent to a section with a green classification or with a yellow/red classification are merged. This results in three area, named CaBe-RWS (all green sections, representing a decrease over the problem period), CaBe-EUP and CaBe-MV1 (both all yellow/red sections, representing an increase over the problem period).

Figure 3.12 depicts the related graph of each of the areas. Looking at the graph 'total' it is clear that there is no increase in maintenance dredging volume observed over the problem period. This means that the problem as experienced by PoR is not the cause of an additional sediment supply to CaBe-system. While CaBe-MV1 shows an increase over the problem period (resulting in the problem experienced by PoR), a decrease of the graph representing CaBe-RWS is noticed. The combination of both observations (no increase of total, opposite behaviour areas CaBe-RWS and CaBe-MV1) results in the assumption that a shift of the sedimentation rates of CaBe-RWS to CaBe-MV1 is leading to the increase in maintenance dredging volumes at MV1, experienced as the problem of PoR.

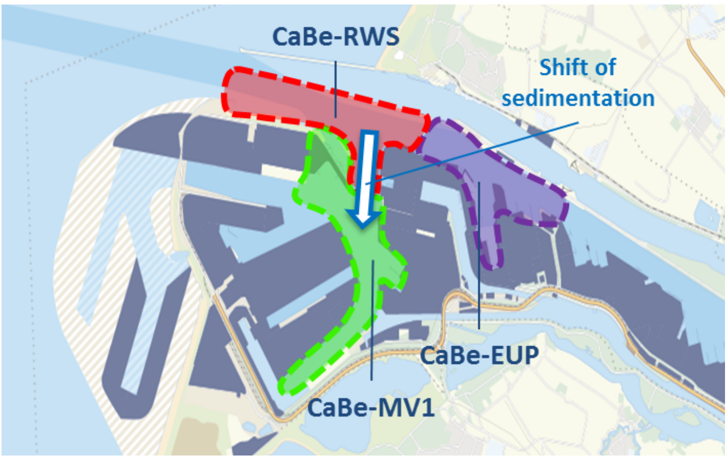

Figure 3.11: Areas within CaBe-system including illustration of shift of sedimentation rates

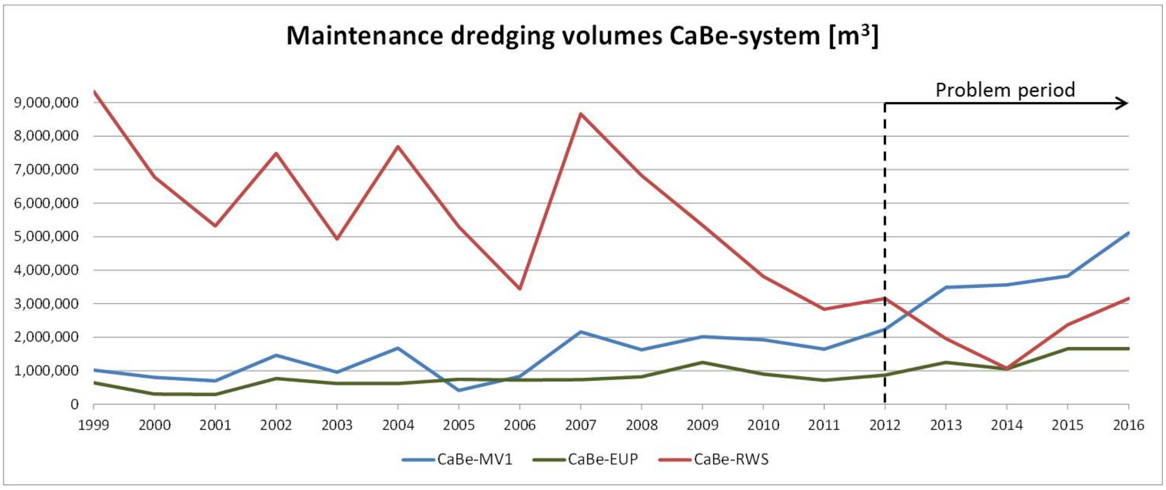

Figure 3.12: Maintenance dredging activity at CaBe-system, definition of the sections is found in Figure 3.11

Based on the five steps of the data analysis it is concluded that: MV1 is the harbour basin responsible for the problem experienced by PoR, which is not the results of an additional sediment supply to the water system MV1 is part of (CaBe-system), but caused by an internal redistribution of the sedimentation rates within the system from CaBe-RWS to CaBe-MV1 as illustrated by Figure 3.11. The outcome of the maintenance dredging volume data analysis will be used in Section D to study its correlation with the event analysis of Section 3.1.1.

3.1.3. Correlation analysis

The aim of the following analysis is to study a possible correlation between the events outlined in Section 3.1.1 and the redistribution of sedimentation rates within CaBe-system over the problem period resulting from Section 3.1.2. In the analysis the results of both sections are merged. To do so the events are plotted in the graphs of the data analysis in which an influence on the maintenance dredging volumes would potential be best visible. In the assumptions derived from this analysis also the influence that an event potentially has on the sedimentation pattern is taken into account. For example a major adjustment to the port layout, e.g. the construction of a new terminal, logically is expected to potential have a more substantial impact on the sedimentation pattern relative to a small intervention, e.g. a new quay wall.

The results are shown in the Figures D.1, D.2 and D.3 of Appendix D. A study of the graphs leads to a strong correlation that the event 'Connection of MV2 to MV1' seem to have with the beginning of the problem period. In Figure 3.13 the graph regarding CaBe-system is shown. On top of that, the event is of a considerable size and potentially has a large influence on the hydrodynamic system of the MV-area. Because of the large size of the event and the strong correlation with the problem period, the expectation arises that the impact of the new harbour basin MV2 are a main, if not the dominant, cause of the problem period as experience by PoR. To provide more details of the event itself a description is given below. As a strong correlation is suggested, also potential effects of the construction of MV2 has on the water system are outlined. This way a the relation with the conclusion of the data analysis, an internal redistribution of sedimentation rates within CaBe-system, can be studied. Logically the connection of the harbour basin of MV2 to MV1 can not be seen apart from the construction of MV2 and hence from here on is taken into account as one event, referred to as 'Construction of MV2'.

Another observation done by the data analysis (step 3, macro scale overview) is the decrease of sections under control of RWS since 2007. No event correlated to the development is found during the analysis and in the figures of Appendix D. Also no indications of a mechanism to describe this phenomenon are found within the scope of this research.

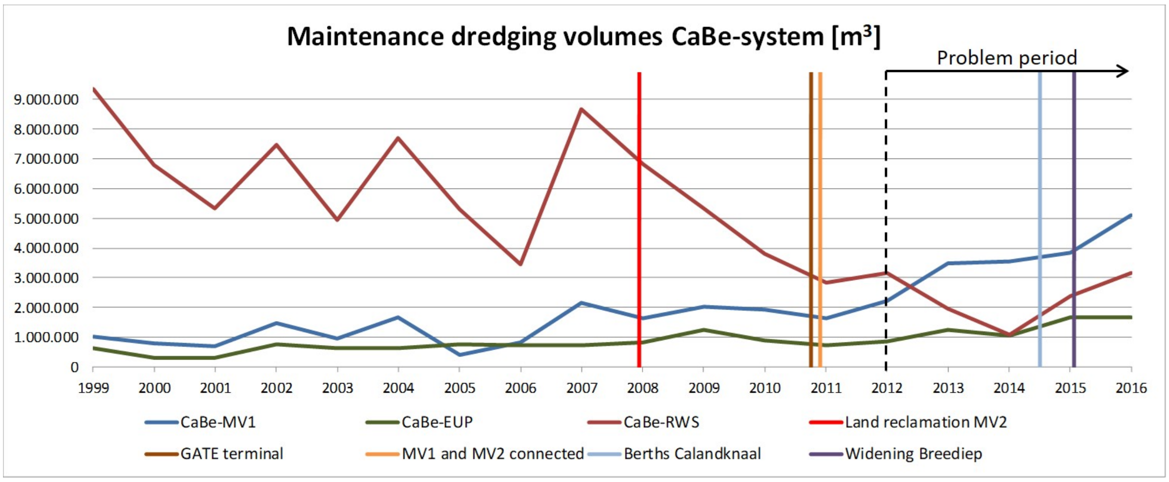

Figure 3.13: Result of the combination of the outcome of the event and data analysis regarding CaBe-system

Construction of Maasvlakte II

Due to the outcome of the correlation study, the event 'Construction of MV2' is further elaborated. The event is explained with use of Figure 3.14. Furthermore the potential consequences to the water system are taken into account.

In the figure two harbour areas are highlighted, MV1 and MV2. MV2 is the most recently built harbour basin of PoR and is constructed by use of a land reclamation. The layout of the land reclamation is shown in the figure with use of the blue line. The land reclamation started in the end of 2008 (event (A) of Section 3.1.1). During the first construction phase a dam (Yangtzedam) divided Yangtzehaven (currently Yangtzekanaal) and MV2, shown as the red line, creating a closed off water basin where currently MV2 is located. In the end of 2011 the Yangtzedam was removed and an open connection between MV2 and MV1 was created. Currently the first terminals of MV2 are under operation, at other locations of MV2 construction works are still in progress.

The construction of MV2 results in an increase of the surface of the entire harbour area (MV1 and MV2), which has an open connection by the Beerkanaal to North Sea climate. An increase of the basin surface logically results in an increase of the tidal filling volume of the MV harbour basins. The tidal filling volume is displaced over a similar time span (tidal-cycle) in and out of the harbour basin, through the exactly same port geometry. Hence an increase of the flow velocities over the tidal cycle is associated with an increase of the tidal filling volume. The impact is expected to be best noticeable in front of the MV1 and at the Beerkanaal, as the velocities quickly dampens once entering the wider harbour basin itself. The highest flow velocities are logically expected at the Beerkanaal, where the tidal flow converges through the smallest section surface.

At the areas described above, the dredging sections of CaBe-RWS are located, which strengthens the suggestion of a correlation. The expected results of the event 'Construction of MV2' in particular affects both areas of interest of this research (CaBe-RWS and CaBe-MV1). To get an idea of the size of the increase a rough calculation is done (also taking into account the filling of Hartelkanaal by tide through MV). The calculation results in an increase of approximately 31.6 mln m^3 per tidal filling in the old situation and 46.4 mln m^3 in the case with MV2 (assumed spring tidal range of 2 metres), which is an increase with a substantial factor of 1.5. Details of the calculation are presented in Table 3.3. An increase of this size is expected to significantly impact the hydrodynamic conditions at the MV-area. A model-based calculation of the tidal filling volume is presented later on in Chapter 4.

In summary, the event 'Connection of MV2 to MV1' is of major interest for further research because of its correlation with the problem period and related potential impact on the hydrodynamic conditions. Hence the event is taken into account as subject of *hypothesis 1.* and is treated this way in the hypothesis selection in Section 3.2.

Harbour area	Wet surface	Tidal filling volume
MV1	9.61 km^2	19.22 mln m^3
Hartel Kanaal	6.18 km^2	12.36 mln m^3
MV2	7.42 km^2	14.84 mln m^3
Total	**23.21 km^2**	46.42 mln m^3

Table 3.3: Details behind the quick calculation of the increase of the tidal filling volume (source: google-maps)

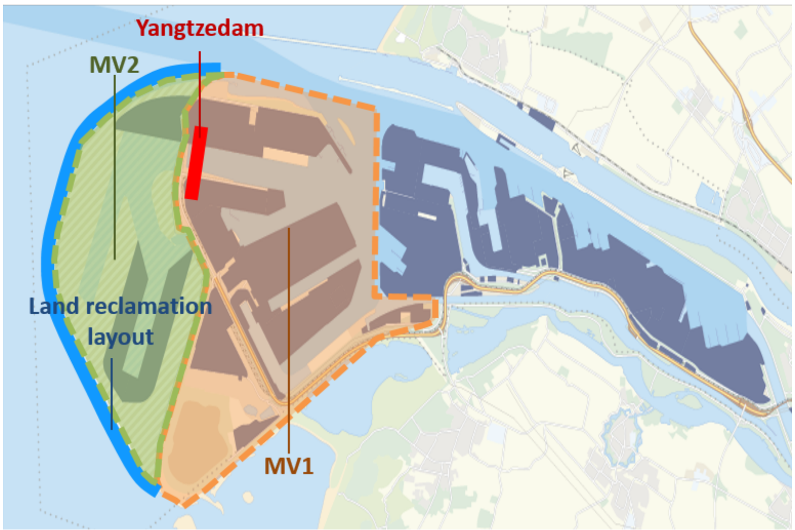

Figure 3.14: Schematic presentation of construction MV2

3.1.4. Maintenance dredging strategy analysis

Regarding *hypothesis 3.*, details of the maintenance dredging strategy are discussed in this section. As described earlier, the maintenance dredging within PoR is under control of two parties, RWS and PoR. An overview is shown in Figure A.2 of Appendix A. This section elaborates on the characteristics of the maintenance dredging activity that could fluctuate over the years. In the end the details made available for this research are described.

Each asset manager is responsible for the maintaining their own dredging sections and has their own contracts with the executing dredging companies. There are two different types of contract to outsource the maintenance dredging activity, a performance and a directing contract. In case of a performance contract the dredging company only receives requirements that are established by the asset manager, such as required depths of dredging sections. The dredging company has to accomplish the requirements, the working method is fully up to themselves and they are paid an allowance agreed in advance (apart from the compliance to the requirements). In case of a directing contract the asset manager controls the approach of execution and directs the dredging company. The dredging company is paid out based on hopper volumes per area.

Other aspects that could result in deviations in maintenance dredging volumes are adjustments to the strategical standards which the asset manager is following. Examples are the additional depth below the required depth applied by the execution of the maintenance works (buffer depth) or the working times.

To conclude, a more strategical decision could be the reason of a change of the maintenance dredging activity. For example as a result of financial management a different approach of maintenance dredging could be followed. An example could be a postponement of maintenance works in case of low budget by the end of the year, resulting in a peak the first month of the following year. All the above described aspects are part of and referred to as the maintenance dredging strategy.

In case of PoR, use is always made of a directing contract and all data on the exact maintained depths over the years is available and provided for this research. Unfortunately the availability of essential information on the dredging strategy of RWS is lacking. The only details on dredging strategy RWS was able to provide for this research is the use of a directing contract since 2014 (without confirming the use of a performance contract the years before) and that the dredging activity from at that moment in time is directed in cooperation with PoR. Also no explanations of the fluctuating behaviour of the maintenance dredging volumes over the last decades (for example the graph of Figure 3.8) could be provided by RWS while working on this research.

The details provided in this analyses are used in Section 3.2 with regard to *hypothesis 3.* to make a selection of the hypotheses that will be subject to a further assessment.

3.2. Hypothesis selection

To find an explanation for the research problem, three hypotheses are defined in Chapter 2 to describe the potential dominant factor responsible for the increase in maintenance dredging volume experienced by PoR. Based on the research analyses of Section 3.1, one of the hypotheses that will be subject to a further assessment is selected in this section. Each of the three hypotheses is treated and assessed on relevance for further research below.

The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in:

1. *Local hydrodynamics by an internal intervention to port layout or geometry*

Based on the outcome of in particular the correlation analysis of Section 3.1.3, *Hypothesis 1.* is specified and selected for the next step of the research phase. The study of the correlation of the event and data analysis in Section 3.1.3 showed that the event 'Construction of MV2' has a strong relation with the beginning of the problem period. Additionally the logical consequences of this event, an increase to the tidal filling volume of the MV harbour basins, in particular affects the local hydrodynamics in the problem area (CaBe-system). The increase of the tidal filling volume is an interesting explanation of the research problem and has to be further researched.

For those reasons the hypothesis is specified to - *'The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2 with an open connection to MV1'* -. In the following section the hypothesis is assessed with the aim to study the potential mechanisms that lead to the internal redistribution of sedimentation rates within the CaBe-system from CaBe-RWS to CaBe-MV1, as the problem is described by Section 3.1.

2. *External factors, resulting in a change of general hydrodynamics or sediment supply*

Based on the outcome of the data analysis of Section 3.1.2 and the correlation analysis of Section 3.1.3 the external factors are assessed not to be the dominant driving force of the increase in maintenance dredging volumes experienced by PoR. In step 2) of the data analysis (Macro-scale North Sea influence) the comparison with the Port of IJmuiden stated that no similarities between the development of dredging volumes was observed at the Port of IJmuiden and PoR, which would have suggested a macro-scale influence of the North Sea. This outcome gave a first indication regarding the North Sea environment. Based on the ratio lines of step 4) 'Water systems' of the data analysis it was concluded that both water systems (CaBe-system and RoWa-system) follow a similar large scale trend over the last decades formed by the external factors. However, no situation as the problem experienced at CaBe-system is observed at RoWa-system. In other words, if a change of the external factors (in the form of a change of the general hydrodynamics within PoR or an increase of sediment supply) would have caused an increase in maintenance dredging volumes at CaBe-system, it is expected to also be influencing the trend at RoWa-system, which is not the case. The outcomes gave a strong indication, but was not yet conclusive. For that reason the external events were also taken into account in the correlation analysis. No strong correlation between the problem period and the occurrence of the most extreme weather conditions was observed. Based on these arguments, the decision is made to exclude *hypothesis 2.* for further research.

3. *Dredging strategy of the asset manager*

Based on the analysis of dredging strategies of both asset managers in Section 3.1.4 it is decided not to include this hypothesis in the next step of the research phase, due to a lack of for research essential information.

However, it is remarkable that the redistribution of sedimentation rates within CaBe system is observed to be around the boundary of the dredging sections under control of PoR (CaBe-RWS) and RWS (CaBe-MV1). Considering that, a change of dredging strategy would be a reasonable option. A change of the approach of the maintenance dredging, for example a decrease of applied buffer depth of the dredging sections under control of RWS, might have resulted in a change of the sedimentation pattern as described above. Unfortunately, as explained in more detail in the maintenance dredging activity analysis, the essential information on the dredging strategy of RWS is missing. For that reason, relevant research is not feasible. In combination with the research time scope the decision is made to leave this hypothesis further untreated.

3.3. Hypothesis assessment

Now one of the research hypotheses resulting from the literature overview of Chapter 2 is selected and specified based on the research analyses of Section 3.1, resulting in:

- The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2 with an open connection to Maasvlakte 1

The hypothesis is subject to an assessment in this section. The assessment is conducted based on the hydrodynamic flow model that is part of OSR. First a detailed description of OSR itself is given (Section 3.3.1). Subsequently the details of the verification of this model are outlined (Section 3.3.2). Finally the hypothesis assessment method is elaborated (Section 3.3.3).

3.3.1. OSR

OSR is a collection of pre-processing tools, two hydrodynamic flow models and post-processing tools used by PoR to forecast the hydrodynamic conditions within PoR, mainly used for ship navigation. The hydrodynamic models are SIMONA applications. SIMONA (SImulatie MOdellen NAtte waterstaat) is developed by RWS and is a collection of mathematical models to solve the hydrodynamic processes. The core of OSR are the two hydrodynamic models which compute water levels, flow velocities and salinity.

- The 2D Port-model - This model covers a large part of the North Sea in front of PoR and the related rivers. The aim of this model is to provide the boundary conditions for the detailed 3D NSC model.
- 3D NSC model - This model is located within the 2D Port-model and describes the port geometry in more detail. The model uses 10 layers that are from here on described with K=1:10. 1 Represents the upper layer, 10 the bottom layer.

In Figure 3.15 the areas covered by both models are visualised. An interactive forecast of OSR can be found at `mx-systems.nl/osr/`.

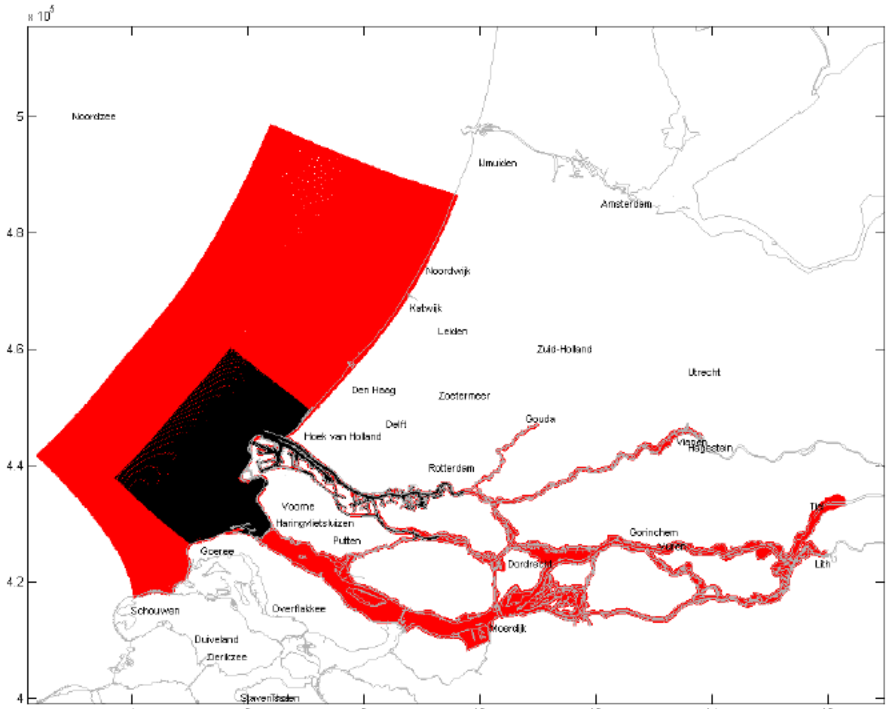

Figure 3.15: Area of the NSC model in black and Port-model in red [Rotsaert, 2009]

3.3.2. Model verification

The OSR models are thoroughly verified and validated, reference is made to the verification report written by [Rotsaert, 2009]. Therefore, the outcome of the OSR models in the form of flow velocity, tide and salinity is assessed accurate and reliable for this research. A brief summary of the subjects of interest is outlined below.

- The water level calculation is classified as excellent to very good and has in general an outcome of approximately 5 cm lower than water level measured. The standard deviation is calculated to be in the range of 3-10 cm
- Flow velocities are classified as excellent to very good and have a slight deviation of the average of 3-10 cm/s with a maximum of 15 cm/s. The standard deviation is generally in the range of 14-21 cm/s
- Regarding salinity the model is assessed to be very accurate. By comparing the outcome of the NSC model to measurements, the model is assumed to be very capable to describe complex situations. The model is assessed as very accurate and versatile, and capable of calculating a large variety of situations in many areas

3.3.3. Method

The hypothesis - *'The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2 with an open connection to Maasvlakte 1'* - is subject to an assessment based on two simulations done with use OSR. The objective is to find the driving mechanism leading to the internal redistribution of sedimentation rates within the CaBe-system from CaBe-RWS to CaBe-MV1 as described in Section 3.1.

The two OSR simulations are run with each a different layout of the MV-area. Simulation A includes the old layout of MV1. Simulation B includes the current layout of MV2. Apart from the MV layout, the entire current PoR layout is used for both simulation. This means that in both simulations all other internal events mentioned in this report are included in the model (such as the widening of Breeddiep and GATE terminal). This way the model only presents differences that fully rely on the hypothesis that is being assessed, the construction of MV2, and a best insight into the impact of purely MV2 is created.

For similar reasons, both simulation use the same model input in the form of the boundary conditions. Average boundary conditions are taken into account, as the influence of (extreme) external events is asses not be the dominant driving mechanism of the problem. Regular conditions give a best presentation of the all-day hydrodynamic conditions within PoR. The details of the boundary conditions used are shown in Table 3.4. Regarding the initial conditions of the model similar input values are used, resulting from the operational model of PoR. This means that the initial conditions of Simulation A are very accurate and a short run-up time is required. Regarding Simulation B this is not per definition the case. To ensure the influence of the of model run-up is excluded, an additional simulation with a substantial long run-up time is processed and compared to the simulation used. The results are described in Appendix E. With use of the appendix it is concluded that the used simulations are not subject to deviations by a shortage on run-up time.

Discharge at Lobith	2300 m^3/s	yearly average [HydroMeteobundel, 2009]
Astronomic tide	2 m (range at spring tide)	conditions January 2018
Wind conditions	3 Bft southwest (continuously)	dominant direction [HydroMeteobundel, 2009]

Table 3.4: Boundary conditions SIMONA simulation

The two simulations are run over the fictional dates from the 1 January to 21 January. With use of the program QuickPlot (part of the Delft3D package) the results of the last 20 days of the OSR simulations are analysed. QuickPlot provides the option to visualise the outcome of a parameter of a simulation in the form of a recording of an overview map of a layer K over time, or as a graph at a measuring station over depth and/or time. Both options are used for analysis of the results. Figure 3.16 presents an example of an overview map of the area that is assessed in combination with the locations of the measuring stations used for analysis. The parameters that are being assessed are treated below. The consequence of the construction of MV2 in the form of an increase to the tidal filling volume is expected to be the driving force of a change to the hydrodynamic conditions within CaBe-system. For that reason the focus of the parameters elaboration below is in particular on the impact of the tidal fillings increase.

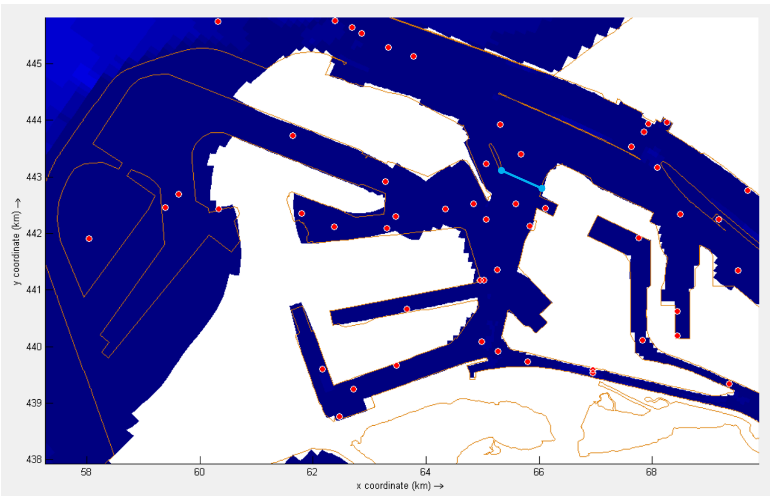

Figure 3.16: Measuring stations within QuickPlot within the area of interest

Tidal filling volume

As described in Section 3.1.3, in particular the increase of the tidal filling volume resulting from the construction of MV2 is expected to have a substantial impact on the hydrodynamics of CaBe-system. In Section 3.1.3 a rough calculation of the tidal filling volume is performed to provide an impression of the order of magnitude of the increase. The calculation was done by multiplying the surface of the harbour basins with the maximum tidal range from theory. The outcome was an increase of the tidal filling volume from 31.6 mln to 46.4 mln m^3 per tidal filling, which is an increase with a factor of 1.5. Now a flow model simulation is available, an accurate model-based calculation of the tidal discharge is done. The rough calculation is done over a fictional transection located at the connection of CaBe-MV1 to CaBe-RWS for a tidal range of 2 metres (mean spring tidal range). A similar calculation will be done with use of Quickplot. More details of the calculation are given in the following chapter. The increase is expected to be in the same order with magnitude as resulting from the rough calculation.

Water level

The water level over the area of interest is an important parameter, as a deviation to it by the construction of MV2 would indicate major changes to the hydrodynamic conditions. The propagation of the tidal wave through the port area determines the resulting water level variation at different locations. An adjustment to the port layout might hence result in differences to the water level variation over tide. The rise and fall of the water level over the area of interest are analysed and compared to the water level at the North Sea to get an impression of how the tide propagates. Changes over both height and over time are of importance for a right understanding of the behaviour of the water system. The water level over the area of interest is subject to analysis with use of several measuring stations, plotting a graph over time. A difference of the water level over time and height within MV might result from the analysis, but is not expected to be noticeable considering the extent of the event.

Salinity

The salinity rates and the resulting density gradients are of interest as they provide a better understanding of the hydrodynamics within CaBe-system. In particular in the form of flow pattern en flow velocity profile over depth. As explained within Section 2.3 differences in salinity can result in both vertical and horizontal density gradients. A strong vertical density gradient would indicate a stratified environment and the therewith related hydrodynamic conditions. A horizontal density gradients is in particular of interest as it is the driving factor of the estuarine circulation.

An increase to the tidal filling volume results in higher mixing rates of fresh and saline water due to more unstable stratification (Figure 2.5) and so a change of the density gradients over the area of interest is expected. The density gradients are analysed with use of measuring stations plots of the salinity profile over depth. As the density profiles vary over the tidal cycle several points in time are analysed. For reporting use is made of the most extreme salinity profiles over the tidal cycle to make clear the differences. The moment in time is during slack tide.

Horizontal flow velocity

As described in Section 2.3, the velocity profile over depth multiplied with the sediment concentration profile result in the sediment transport profile. Section 2.2 describes that depending on the particle size, the flow velocity determines if a particle is picked up, kept in suspension or settles. The direction of the horizontal flow logically determines in what direction the particle (if suspended) is transported. It might be clear that an accurate analysis of the horizontal flow is essential for this research. The parameters mentioned above are each in its own manner of influence to the flow pattern. The relation between the different parameters is subject to analysis to ensure a right understanding of the hydrodynamics within the system.

As already briefly described within Section D, an increase of the horizontal flow velocity is the logical result of an increase of the tidal filling volume. A larger volume of water is displaced through the same port geometry over the same tidal period. An increase of the magnitude of velocity is expected to be in the same order of magnitude as the increase of the tidal filling volume. Beside the velocity itself, also an the direction of the flow velocity over the tidal cycle is subject to analysis.

Several options to visualise the horizontal flow velocity are provided by Quickplot. Mainly use is made of maps that present both the magnitude (in colour) and direction (arrow) of a specific layer K. For analysis recordings over time of these maps are used to provide a clear profile of the development of the horizontal flow velocity of different layers over the tidal cycle. For more details of a specific location, additionally use can be made of (absolute) flow velocity profiles over depth. For reporting use is made of two specific moments in time that represent the maximum flow velocities occurring in the simulation, one during ebb (from here on referred to as *ebb-case*) and one during flood (from here on referred to as *flood-case*). The highest tidal range (spring tide) is observed at January 20 (fictional date). The ebb- and flood-case are shown in Figure 3.17 and take place at respectively 8:00 and 16:00. The decision for these moments in time is made based on the fact that the interest of this research is on fine sediments, which are subject to settling lag as described in section 2.3 and therefore extra sensitive to the highest flow velocities occurring. Besides, differences in horizontal flow velocity between Simulation A and B are expected to be best visible comparing both most extreme cases. Regarding the other parameters use is made of the same date in the model (January 20).

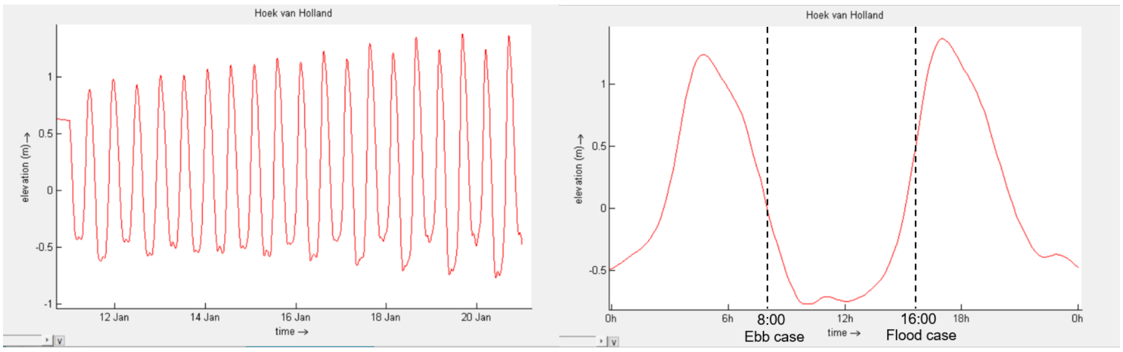

Figure 3.17: Ebb-case and flood-case at HoH at the fictional date 20 January 2018

The two research analyses presented in the beginning of this chapter result in combination with the correlation analysis in the selection of one of the hypotheses defined in Chapter 2. The last step of the research phase is the elaboration on the assessment method. The results of this method are taken into account for the result phase of the research. The result phase is presented and discussed in the following chapter.

4
Results

In Chapter 3 the research analyses lead to the selection of the hypothesis - *'The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2 with an open connection to Maasvlakte 1'* - for further assessment. The assessment method is described in 3.3.3. The results are presented and discussed in this chapter.

The chapter starts providing a clear overview of the hydrodynamic system within CaBe-system in the situation before MV2 in Section 4.1. Use is made of Simulation A described in the hypothesis assessment method. Subsequently a description of the current hydrodynamic conditions, including MV2, is provided in Section 4.2. The section is based on comparing Simulation B with Simulation A and focusing on the differences to the general hydrodynamic conditions resulting from purely the construction of MV2. This way insight into the consequences of the construction of MV2 is provided.

The hydrodynamic conditions of the water system in both simulations are described with use of the parameters outlined in Section 3.3.3: tidal discharge, water level, salinity and horizontal flow condition. The sections are subdivided into subsections, each describing one of the parameters. The first time a parameter is treated a description of the method of analysis is given. All figures presented within this chapter are compiled with use of Quickplot. In Figure 4.1 an overview of the locations of the measuring stations and transection used for reporting is given. Additional stations within the area of interest used for analysis together with graphs describing the simulation results are captured within Appendix 4. Essential figures are presented in the chapter itself.

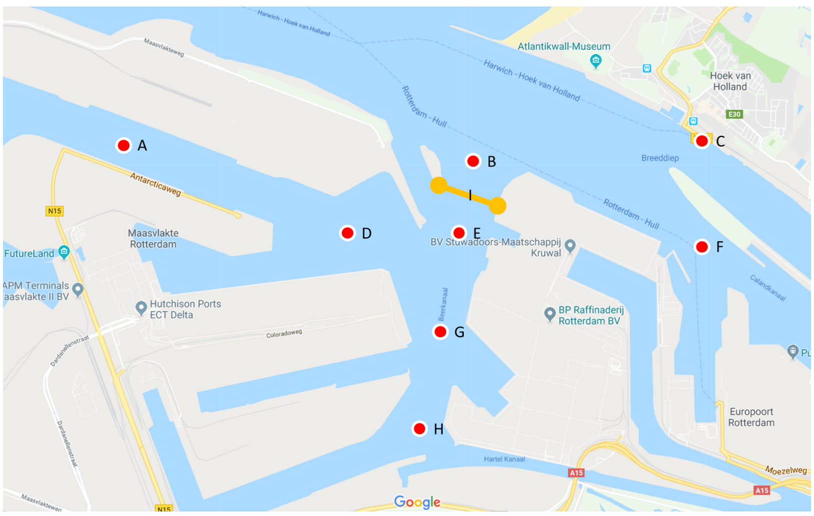

Figure 4.1: Measuring stations and transection within the area of interest used for reporting

The stations shown in Figure 4.1 are outlined below with a brief description. Between brackets the area where the station is located regarding CaBe-system.

- A - Yangtzekanaal Torline (CaBe-MV1)
- B - Beerkanaal Monding (CaBe-RWS)
- C - Hook of Holland (CaBe-RWS)
- D - Europahaven voor (CaBe-MV1)
- E - Papegaaienbek Beerkanaal (CaBe-MV1)
- F - Beneluxhaven Calandkanaal (CaBe-EUP)
- G - 6e Petroleumhaven Beerkanaal (CaBe-MV1)
- H - Beergat (CaBe-MV1)
- I - Transection used for the calculation of the tidal filling (connection CaBe-RWS to CaBe-MV1)
- (-) Maas-C Boei is located at the North Sea approximately ten kilometres in front of PoR and is used as reference point (North Sea)

4.1. General hydrodynamic conditions

To provide a clear view on the general hydrodynamic conditions within CaBe-system, first an overview of the parameters in the situation before the construction of MV2 is provided. It is important to realise that Simulation A is not literally the situation before the construction of MV2. All events since the construction of MV2 are included in the model run of Simulation A. Hence, apart from the MV-area, Simulation A contains the current layout of PoR. This approach is used to exclude other factors of influence and purely focus on the differences resulting from the assessed event as mentioned in Section 3.3.3. The results of each parameter are treated separately.

4.1.1. Tidal discharge

As described in Section 3.3.3, the increase of the tidal filling volume as a result of the construction of MV2 is of main interest. A rough calculation of the increase of the tidal filling volume is done in Section D. With use of the simulations an accurate model-based recalculation is done. This section presents the tidal filling volume calculation before the construction of MV2, based on Simulation A.

Quickplot provides the possibility to do a cumulative calculation of the tidal discharge over in the model standard implemented transections. In this case use is made of the transection as depicted in Figure 4.1. It must be noted that the transection does not take the tidal discharge passing through Nijlhaven (the harbour terminal directly west of the transection) into account. The calculated tidal discharge will logically be lower than the total tidal discharge. Nevertheless, as will be seen in further analysis, the tidal filling discharge through the Nijlhaven is relatively low. Nijlhaven contains a shallow basin compared to the connection from the waterway to the MV, where the transection is located. Later on it will become clear that the main flow is marine driven and concentrated at the lower layers of the model. On top of that the transection surface of Nijlhaven is only a slight fraction of the connection between the waterway and the MV. Finally, in particular the factor of tidal filling increase is used for this research. This factor is expected to be accurate, as it is assumed that the ratio of flow distribution over both transections (transection used for calculation and transection of Nijlhaven) is equal in both situations.

The tidal discharge of Simulation A is 30.0 mln m^3 per tidal filling based on the model-calculation. The calculation is done over January 20. The outcome is in the same range as the value resulting from the rough calculation done in Section 3.1.3 (31.6 mln m^3), this implies that a good understanding of the actual situation is used as a basis for the expected consequences.

4.1.2. Water level

The water level over the area of interest is an important parameter with a major impact on the hydrodynamic conditions. The propagation of the tidal wave through the port area determines the resulting water level. For that reason the intervention to port layout by construction of MV2 might result in a differing water level variation. For analysis the water level variation of January 20 is set out over time at measuring stations mainly around the boundaries of the CaBe-system. Additionally stations further upstream and at the North Sea are added to the same graphs, to study where differences are noticeable. For reporting use is made of the measuring stations HoH (taken as standard in Section 2.1), Yangtzekanaal Euromax and Beergat. The results are shown in Figure 4.2.

The analysis of the graphs lead to the conclusion that over the entire area of interest the water level is observed equal over time, with possible a slight deviation of 0-5 centimeters in height. This deviation is only shortly noticed at the most extreme water levels (slack tide) and can be assigned to reflection of the tidal wave at the harbour basins end. For that reason it is assumed that the tidal wave propagates equally over CaBe-system. The water level development has no deviation compared to the water level measured at HoH, which can be explained by the open connection with, and short distance to, the sea. An extension of the studied area to Hartelkanaal provides similar results and corresponds to the water level variation observed within CaBe-system. More inland the first stations with a slight deviating outcome are found. The differences are noticeable in both height and slightly time. Examples are the measuring stations at Oude Maas (upstream end of Hartelkanaal) and Botlek Bridge, where the tidal wave can propagate through other river branches such as the Rotterdam Waterway.

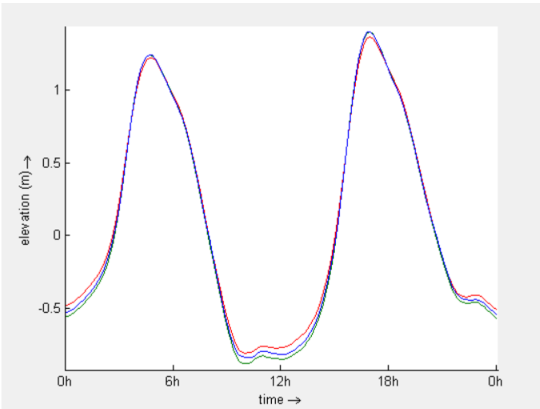

Figure 4.2: Water level plotted over time at HoH (red), Beergat (blue), Yangtzekanaal Euromax (green)

4.1.3. Salinity

The salinity rates and resulting density gradients are of interest as they provide a better understanding of the hydrodynamics within CaBe-system, in particular in the form of the flow pattern and flow velocity profile over depth. As explained within Section 2.3 differences in salinity can result in both vertical and horizontal density gradients. A strong vertical density gradient would indicate a stratified environment and the therewith related flow pattern. Horizontal density gradients in particular are of interest as it is the driving factor of the estuarine circulation.

Quickplot provides the opportunity to plot the salinity profile over depth at the measuring stations (vertical density gradient). Unfortunately QuickPlot is not able to plot a salinity profile of a layer over space (horizontal density gradient). For that reason multiple salinity profiles over depth at several locations are taken into account to provide insight into the distribution of the salinity rates over the horizontal. For reporting use is made of the station the measuring stations Maas-C Boei (representing the North Sea, approximately ten kilometers in front of PoR as reference), Beerkanaal Monding (representing CaBe-RWS), Beneluxhaven Calandkanaal (representing CaBe-EUP) and 6e Petroleumhaven (representing the CaBe-MV1). The report uses the salinity profiles of the two most extreme moments in time. In case of salinity these are the slack tides. During ebb and flood the mixing of fresh and saline water is in progress. The salinity profiles reach an extreme at slack tide when the water movement is relatively low and the mixing rates are reversed. The slack tides take place at January 20, 10:00 after ebb and 17:00 after flood (Figure 3.17), from here on referred to as low-tide and high-tide respectively. The results on base of Simulation A are described below. Subsequently distinction is made between vertical density gradients and horizontal density gradients to discuss the results. Additional figures are found in Appendix F.

An analysis of the salinity profiles over depth indicates that differences between the bottom layer and upper layer are clearly visible. The results are shown in Figure 4.3. On the left the low-tide salinity profiles are found, on the right high-tide. Logically the salinity profile at the North Sea is overall salt with a slight variation at the upper layer between 30-33 ppt (units of parts per thousand) over the tidal cycle. The other salinity profiles located at PoR vary from 18-23 upper layer to 30-32 at the bottom layer during low-tide and 20-22 at the upper layer to 29-31 at the bottom layer during high-tide. In Table 4.1 that will be treated later on details are summarised per location.

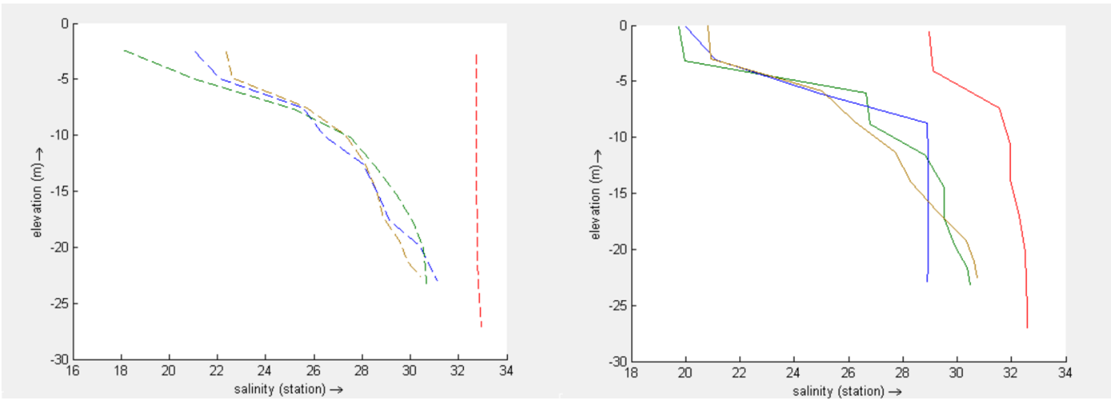

Figure 4.3: Salinity profiles over depth at low-tide (dashed line) and high-tide (solid-line) of the measuring stations Maas-C Boei (red), Beerkanaal Monding (blue), Beneluxhaven Calandkanaal (brown) and 6e Petroleumhaven (green)

Vertical density gradient - Regarding the vertical density profile it is clear that over entire CaBe-system a vertical density gradient is present, resulting in a stratified environment. The differences between the upper and lower layer are approximately 10-12 ppt at low- and high-tide. The gradient of the low-tide graph is more linearly. The high-tide profile has a sharp gradient, indicating a clear separation of the lower and upper layers.

Horizontal density gradient - An analysis of the results learns that the differences in salinity over the horizontal result in a slight horizontal density gradient at the bottom layers from MV to the North Sea. At high-tide the horizontal density gradient has as expected the highest outcome. It is explained by the unstable tidal filling, described in Section 2.3. As the next section will show, the flow at the upper layer is a constantly seawards directed by the estuarine circulation in combination with the river fresh water discharge. The salinity profiles over depth at different distances of the North Sea are as expected. The density of the lower layers decreases moving from the North Sea into the port, ending at the MV where the lowest densities are found. Between the area under control of RWS and Europoort only slight differences are noticeable, which can be explained by the wide and open connection and close distance to each other.

4.1.4. Horizontal flow velocity

By the description of the parameter horizontal flow velocity of Section 3.3.3 it is clear that an accurate analysis of this parameter is essential for the research problem. The relation to the results of the parameters treated above are studied and discussed. By doing so a right understanding of the hydrodynamics within the system is provided.

From the recordings of the several layers describing the magnitude and direction over the area of interest used for analysis, the most extreme moments in time (ebb- and flood-case) are shown in the Figures 4.4 and 4.5. Again only the most essential figures are included in this chapter, while the entire simulation is subject to analysis. For reporting use is made of the ebb-case and flood-case as described in Section 3.3.3. The parameter horizontal flow velocity is split up in the aspects magnitude and flow direction. Both logically differ strongly per measuring station. All figures used for analysis are found in Appendix F. As will become clear later on, the flood-case is of significant importance for a right understanding of the problem.

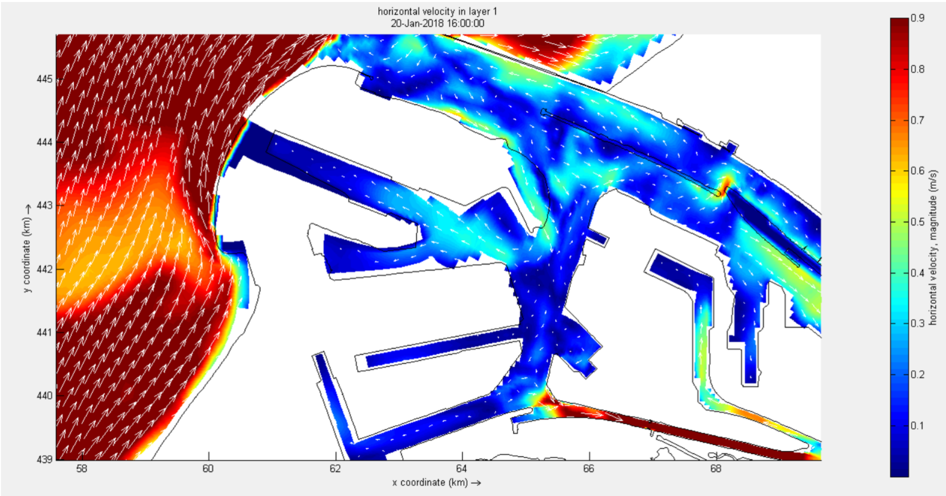

Figure 4.4: Overview of the horizontal flow velocity at the upper layer of the flood-case of Model Simulation A

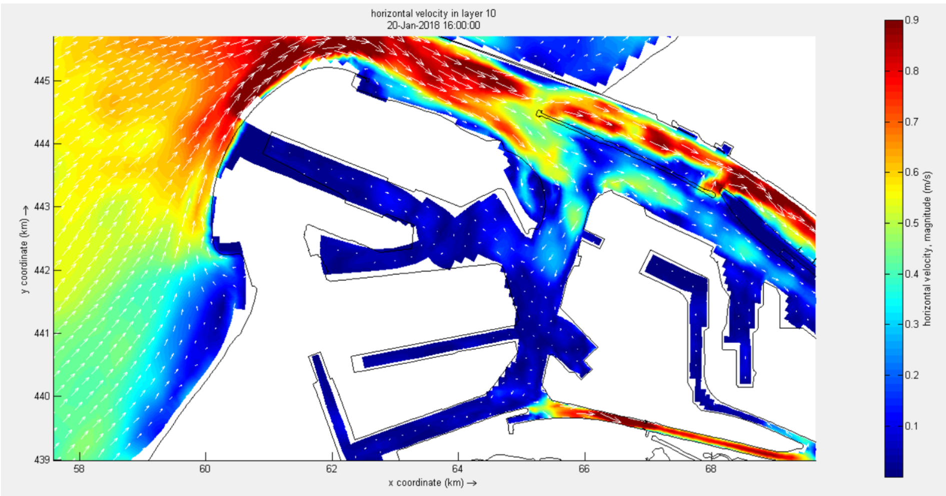

Figure 4.5: Overview of the horizontal flow velocity at the bottom layer of the flood-case of Model Simulation A

Magnitude: By the salinity analysis it is clear that a vertical density gradient is present in the system. This stratified environment is also visible looking at the horizontal flow velocities. At the lower layers significant high velocities are found during the flood-case, none to slight velocities during the ebb-case. The opposite takes into account for the upper layers. Figure 4.6 presents a good example of the horizontal flow velocity magnitudes over the depth in both cases (ebb and flood). During flood an intrusion of salt water beneath the fresh water is observed. During ebb a profile is found with slight velocities at the bottom, linearly increasing up to 0.5 m/s at the upper layer. Please be aware that the figure presents the absolute magnitude of the horizontal flow velocity and no direction is displayed. This means that the velocity at the upper layers can be directed opposite to the bottom layers. Insight into the direction is provided with use of the maps in Figures 4.4 and 4.5.

Regarding the location, based on Figure 4.5 it can generally be stated that the velocities at CaBe-RWS are relatively high compared to the velocities measured at CaBe-MV1. This is mainly due to the more narrow geometry the tidal wave has to propagate through at the waterways. The MV basin is more wide and velocities are quickly dampened.

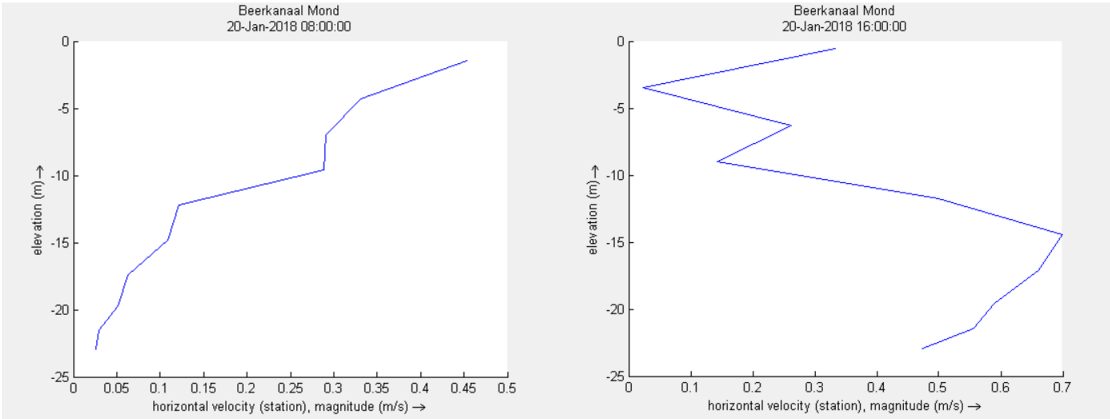

Figure 4.6: Horizontal flow velocity profile at Beerkanaal Monding in front of MV

Direction: The results are, as far as clear at this point, in line with the outcome of the parameters above. The salinity profiles over depth are visible in the flow pattern over the area of interest when looking at the maps of the bottom and upper layer in both the ebb- and flood-case (Appendix F. As the sediment concentration is highest at the bottom layers, in particular the behaviour of the bottom layer is of interest for this research.

The horizontal flow induced by tide is strongly concentrated at the lower layers over the entire area of interest. It turns out that at the bottom layer the horizontal flow is during the entire tidal cycle mainly directed landward (although with low velocities at the ebb-case). During ebb, the outflow of water is concentrated over the upper layers of the model. More details of the flow velocity profiles over depth are found in Appendix F. The results learn that the bottom layers of the system act like kind of a sediment pump, continuously pumping sediments from North Sea and waterway into MV1. The top layers that are of less influence to the net sediment transport are mainly directed seawards over the tidal cycle.

For the research problem in particular the flow at the connection between the MV and the waterway is of interest, as here the biggest differences due to the increase of the tidal filling volume are expected. For that reason the horizontal flow velocity profile of Papegaaienbek Beerkanaal (located in the middle of the connection) is plotted in Figure 4.7. Again the stratified environment is clearly visible comparing the ebb- and flood-case.

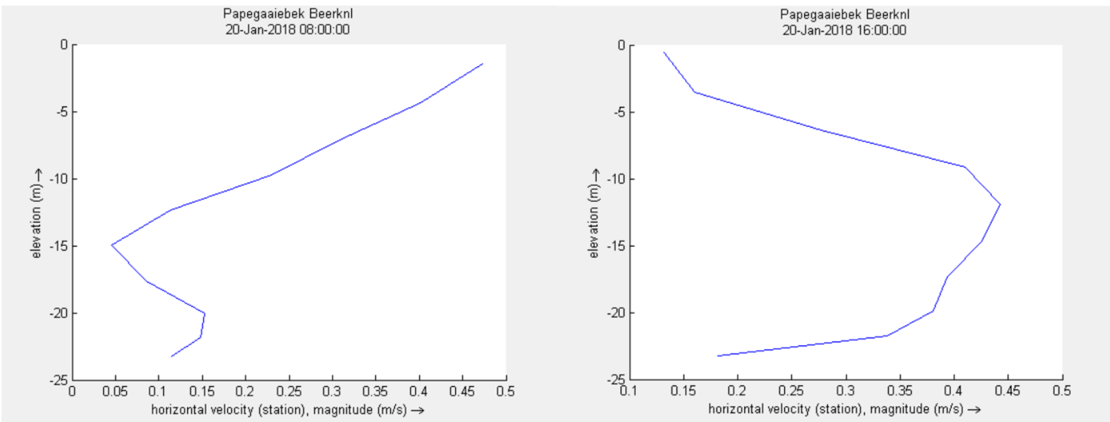

Figure 4.7: Horizontal flow velocity profile at Papegaaienbek Beerkanaal Monding in the connection of MV to the waterway

4.2. Hydrodynamic conditions after construction MV2

As described, the construction of MV2 is expected to have a substantial impact on the hydrodynamics of CaBe-system and hence on the sedimentation rates within the system. This section outlines the changes to the hydrodynamic conditions of the system according to the flow model simulation. This is done by comparing the results of Simulation B (including MV2) to Simulation A (excluding MV2), on which Section 4.1 is based. The only difference between both simulations is the construction of MV2. The entire PoR lay-out, initial and boundary conditions are exactly the same. In other words, all differences between both simulations are fully the result of the construction of MV2.

Per parameter the section first recapitulates the expected impact of the construction of MV2. Subsequently an analysis of the differences to the 'general' hydrodynamic conditions described in Section 4.1 is done. The last step is to relate the differences to the expectations and find a clarification based on the theoretical background of Chapter 2. The analysis takes into account the full simulation. For reporting use is made of the same measuring stations and moments in time as in Section 4.1 to best point out the differences. The aim of the section is to provide a thorough understanding of the development of the hydrodynamic conditions of CaBe-system by the construction of MV2, so in the final research phase (Chapter 6) these findings can be related to the origin of this research and answer the main research question.

4.2.1. Discharge

The aim of the hypothesis assessment is to study the possible relation between the event 'The construction of MV2' and the research problem as defined by Chapter 3. The decision to further study the relation between this specific event and the research problem relies on several findings that are further elaborated in Chapter 3. Apart from the correlation of the moment in time the event and the problem phase took place, the expected impact of the event on the water system is in line with the occurrences noticed by the research analyses. The expected impact is based on in particular the consequences of an increase of the tidal filling volume. For that reason first a calculation of the increase of the tidal filling volume based on the model simulations is done. In the following subsections the calculated increase is related to the development of the other parameters of interest. By doing so, it can be concluded that indeed the impact of the tidal filling increase associated with the construction of MV2 is the driving mechanism responsible for the change of the hydrodynamic conditions and no other main factors are overlooked.

A similar calculation as described in Section 4.1.1 regarding tidal discharge is done with Simulation B. The outcome of the new tidal filling volume calculation is 44.2 mln m^3. Assuming that the tidal filling volume passing by the Nijlhaven increases in a similar proportion, the increase factor of the tidal filling volume is stated to be 1.4 (30.0 mln m^3 in Simulation A). This of the same order of magnitude as the outcome of the rough calculation (1.5), which means the potential consequences of the construction of MV2 are done based on a right understanding of the size of the event. A good understanding of the problem in an early stage would potentially result in a more accurate formulation of the expectations of the impact and hence forms a good base of a right approach to the model results.

4.2.2. Water level

As described in 3.3, it is expected that no significant differences to the water level variation occur as a result of the construction of MV2. The results are in line with the expectation, as can be seen in Figure 4.8. It must be noted that the small differences noticed in Section 4.1.2 regarding the water level at slack tide are slightly higher with 0 - 10 centimeters. This can be explained by reflection of the tidal wave at the harbour basins end of the larger tidal filling volume. Result is a (relatively small) additional increase of the tidal filling volume.

The most important finding done is the observation that the tidal wave is noticed at exactly the same moment in time over the area of interest as before the construction of MV2. This means that the tidal wave propagation within CaBe-system is similar as before the construction of MV2. In the the other case it would have had a major impact on the hydrodynamics of the system. It is concluded that by the open connection to and short distance from the North Sea no differences in the water level variation over the tidal cycle at the area of interest result from the construction of MV2.

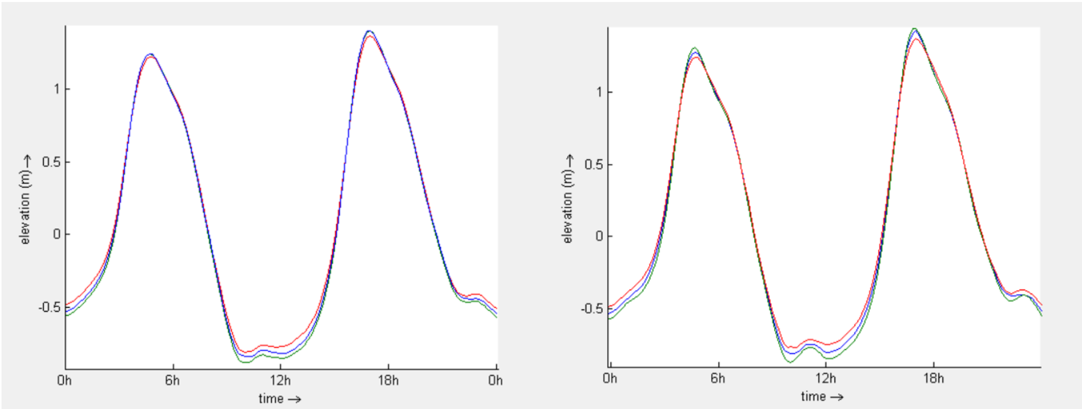

Figure 4.8: Measured water level simulation A (left) and B (right)

4.2.3. Salinity

In Section 4.1.3 it was found that the area of interest contains a stratified environment, which is noticed the strongest during high-tide as a result of unstable tidal filling. A horizontal density gradient is best visible over the North Sea towards the MV. It is expected that the increase of the tidal filling volume of the MV results in a larger unstable filling with the consequence of higher mixing rates at MV. A higher mixing rate would mean a lower vertical density gradient and hence a less stratified basin. In turn a lower vertical gradient would result in a higher vertical density gradient over the North Sea to the MV over the lower layers. To best describe the actual behaviour regarding these subjects, the measuring station representing MV and the area under control of RWS are highlighted in this section.

The results are summarised in Table 4.1 and correspond to the expectation, even though it is just slightly visible. To describe the findings of the analysis use is made of Figure 4.9. Again the dashed-line represents low-tide, the solid-line high-tide. The name of the measuring station is shown above the corresponding graph. In blue the graphs resulting from Simulation A (geometry of MV1), in red Simulation B (geometry of MV2).

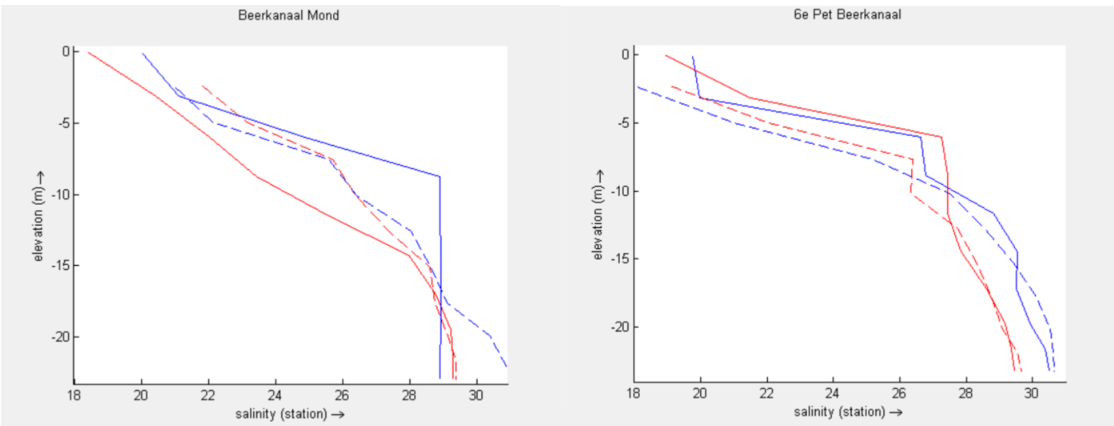

Figure 4.9: Salinity profiles over depth at low-tide (dashed line) and high-tide (solid-line) of the measuring stations Beerkanaal Monding and 6e Petroleumhaven Beerkanaal of Simulation A (blue) and Simulation B (red)

	Sim. A	**Sim.B**
CaBe-RWS - *upper layer*	20-21 ppt	18-22 ppt
CaBe-RWS - *lower layer*	29-31 ppt	29 ppt
CaBe-EUP - *upper layer*	21-23 ppt	20-22 ppt
CaBe-EUP - *lower layer*	30 ppt	30 ppt
CaBe-MV1 - *upper layer*	18-20 ppt	20 ppt
CaBe-MV1 - *lower layer*	31 ppt	29 ppt

Table 4.1: Overview of salinity rates within CaBe-system in case of Simulation A and Simulation B

Vertical density gradient - Regarding the area under control of RWS (Beerkanaal Monding) none to slight differences at the bottom layers are visible at both bottom layers. But in the middle of the water column a lower outcome of the density is visible which continues to the water surface. The development of the density gradient is also more smoothly, and hence less clearly stratified. The results at the MV area (6e Petroleumhaven Beerkanaal) differ at some points. Here the density of the lowest layers has clearly a lower outcome of approximately 1 ppt which keeps continues until the top layers. The top layers itself show very roughly a same profile as in the old situation. This is a logical result of the increase of unstable tidal filling. It is questionable if these slight differences are affecting the stratified flow pattern observed in Section 4.1.4. In the next section this is treated into further detail.

Horizontal density gradient - As mentioned before, there is no option to plot horizontal density gradient lines in Quickplot. For that reason the analysis is based on the graphs and description of the vertical density gradient above. In general an increase of the steepness of the vertical density profile is visible at in particular the MV (in other words a lower density at the bottom layers, higher at the upper layers). Assuming that the salinity profile of the North Sea is similar, the results described above indicate a stronger horizontal density gradient at the lower layers in particular over the waterway in front of the MV into the MV. Even though the differences are of a low order of magnitude an increase of the horizontal density gradient can result in a strengthening of the estuarine circulation. This would mean an increase of the horizontal flow velocities over the area of interest and a larger water circulation. Higher flow velocities are expected at in particular the bottom layers. It must be noted that this circulation is not visible in the calculation of the tidal discharge of Section 4.2.1, as it results in an increase of both the in- and outflow through the transection.

4.2.4. Horizontal flow velocity

As mentioned before, the main subject of the assessment is the development of the horizontal flow velocity after the construction of MV2. Based on the results of the increase of the tidal filling volume described in Section 4.2.1, an increase with a factor of 1.4 to the horizontal flow velocity can be expected. Additionally the development of the horizontal density gradient can have its impact on the horizontal flow velocity as the estuarine circulation is strengthened.

To best point out the differences compared to Simulation A, the results are reported with use of the same figures as Section 4.2.4. The Figures 4.10 and 4.11 present the maps at the flood-case of the bottom and upper layer. Again the horizontal flow velocity is split up in the aspects magnitude and direction. In Appendix F more figures used for analysis are shown.

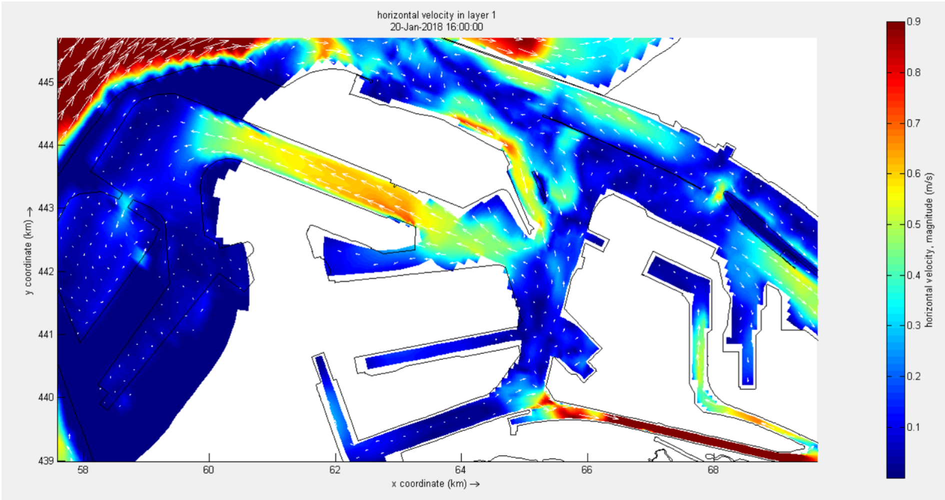

Figure 4.10: Overview of the horizontal flow velocity at the upper layer of the flood-case of Model Simulation B

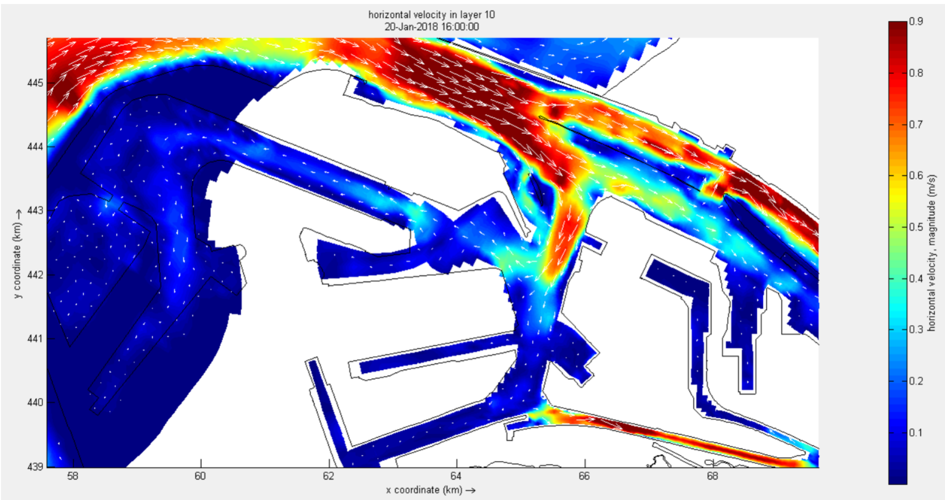

Figure 4.11: Overview of the horizontal flow velocity at the bottom layer of the flood-case of Model Simulation B

Magnitude - A significant increase of the horizontal flow velocity magnitude is measured. Two examples showing the results are given with Figure 4.12 and 4.13. In particular the measuring station within the connection of CaBe-RWS to CaBe-MV1 (Papegaaienbek Beerkanaal) contains an exceptional result with an increase of a maximum velocity of 0.45 m/s up to 0.9 m/s, which is an increase with a factor of 2.0. The outcomes exceed the expected increase based on the tidal discharge calculation. All stations located along the connection between the North Sea and MV2 basin show comparable results. The stations located at MV1 more towards Hartelkanaal (located at the other outer end of MV1) only negligible differences of the horizontal velocity profiles are noticed. The same takes into account for the measuring stations at EUP. The measuring stations in front of MV1 where the tidal wave of both MV and EUP propagates through (for example Beerkanaal Monding, Figure 4.12), show an increase a maximum factor of 1.55. As described, an increase of the horizontal flow velocity was expected, but the order of magnitude measured exceeds the prediction.

The increase of tidal filling volume and the increase of the horizontal density gradient are of impact to this interesting outcome. Other factors of influence will be discussed within the final phase of this research (Chapter 6). Generally it can be stated that a strong increase of horizontal flow velocities is measured, in particular at the area in front of and within the connection from the waterway to MV. Once entering the MV the flow velocity is quickly dampened and only an increase is noticed at the connection from MV1 to the new harbour basin MV2.

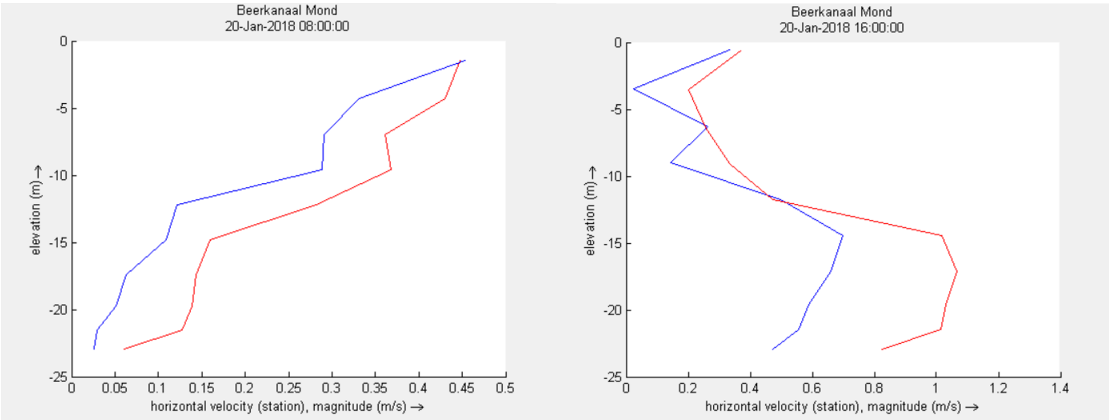

Figure 4.12: Horizontal flow velocity profile at Beerkanaal Monding in front of MV at the ebb-case (left) and the flood-case (right). In blue the profile of Simulation A (layout of MV1), in red the profile of Simulation B (layout of MV2)

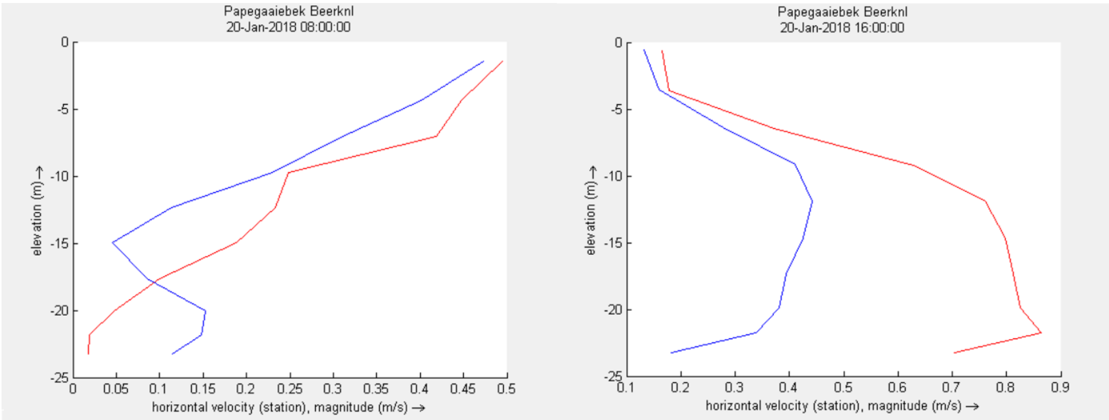

Figure 4.13: Horizontal flow velocity profile at Papegaaienbek Beerkanaal in the connection between MV to the waterway at the ebb-case (left) and the flood-case (right). In blue the profile of Simulation A (layout of MV1), in red the profile of Simulation B (layout of MV2)

Direction - Regarding the direction of the horizontal flow velocity no significant changes are noticed, with exception of Yangtzekanaal (the connection from MV1 to MV2). This is best visible with use of the Figures 4.12 and 4.13. The slight changes to the vertical density gradient caused by the increase of unstable tidal filling are not observed in the form of a change to the horizontal flow direction over different layers. Resulting from the analysis of the horizontal flow velocity it can be stated that the construction of MV2 has no significant impact on the flow pattern.

The following two chapters present the final research phase. The results presented in this chapter lead to the final assessment of the selected research hypothesis and the formulation of the research conclusion. Based on the research conclusion, a reduction measure recommendation is given in Chapter 5. A further elaboration on the research conclusion is given in Chapter 6, together with the research discussion and recommendations for further research.

5

Reduction measure

To provide an answer to the second objective of the main research question, a recommendation of a measure to reduce the maintenance dredging activity for the research specific case is provided in this chapter. The relation between the results of the hypothesis assessment and the outcome of the research analyses are discussed in Section 5.1. This sections is also the base of the research conclusion that is described in further detail in the following chapter. Based on the research outcome, a recommendation in the form of a sediment trap is done. The details of a measure of this form are described in Section 5.2. Finally the potential location of the sediment trap is discussed in Section 5.3.

Apart from the recommended reduction measure, a logical first step to approach the problem has to be mentioned and is of a totally different form. The consequences of the construction of MV2, in the form of a redistribution of the sedimentation rates of CaBe-system, is considered as a problem by PoR. Opposite, the current situation is more favorable for RWS. It is recommended to discuss the possibilities to cooperate, which is already the case regarding several aspects of the maintenance dredging activity, and share the consequences. As a solution of this form lies completely outside the scope of this research, the subject is further left untreated within this report.

5.1. Relation research analyses and hypothesis assessment

The reduction measure recommendation done, is research specific and based on the previous research phases. The relation between the outcome of the research analyses and the hypothesis assessment is discussed in this section. Based on the relation, the selected hypothesis is accepted or declined as the dominant factor responsible for the research problem. The reduction measure recommendation described in the next section is based on this outcome.

The several research analyses lead to the conclusion that the research problem is the result of a redistribution of the sedimentation rates within CaBe-system by the construction of MV2 with an open connection to MV1. The hypothesis assessment describes that the consequences of the construction of MV2 indicate a change of the local hydrodynamics of CaBe-system in particular in the form of an increase to the horizontal flow velocities. The results of both research phases are taken into account and compared to assess the hypothesis - *'The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2'* -.

Figure 5.1 (also depicted in Chapter 3) visualises the development of the dredging activity over the base and problem period based on the data analysis. To compare the results of the hypothesis assessment to the outcome of the research analyses, Figure 5.2 is introduced. The horizontal flow velocity of the bottom layer (K=10) at the flood-case of Simulation A (left) and Simulation B (right) are plotted. In the figure the results of the data analysis are included in form of the green and red rectangle depicted over the maps. The rectangles represent the areas where a decrease (green) and an increase (red) of the maintenance dredging volumes are administrated. The results of the data analysis show a similar pattern as the increase of flow velocities measured with the model simulations. The results can be best explained with use of the following observations:

1. Green rectangle - Decrease of maintenance dredging works, increase of horizontal flow velocity;
2. Brown oval - Strong increase of landward directed horizontal flow velocity;
3. Red rectangle - Increase of maintenance dredging works, no to slight change to horizontal flow velocity;

Together the three observations form an explanation for the mechanism described to be the driving factor of the problem, namely 'a redistribution of the sedimentation rates within CaBe-system (from CaBe-RWS to CaBe-MV1, see Figure 3.11)'. 1) As a result of the increase of the horizontal flow velocity within the green rectangle (CaBe-RWS), a significant part of the sediments that previous were able to settle at that location, are now kept in suspension. 2) The high (harbour basin directed) horizontal flow velocity at the connection of CaBe-RWS and CaBe-MV1 transport the sediments that before used to settle at CaBe-RWS into CaBe-MV1. 3) Once transported to CaBe-MV1, the high flow velocity quickly dampens because of the large harbour basin surface and sediments are able to settle at CaBe-MV1.

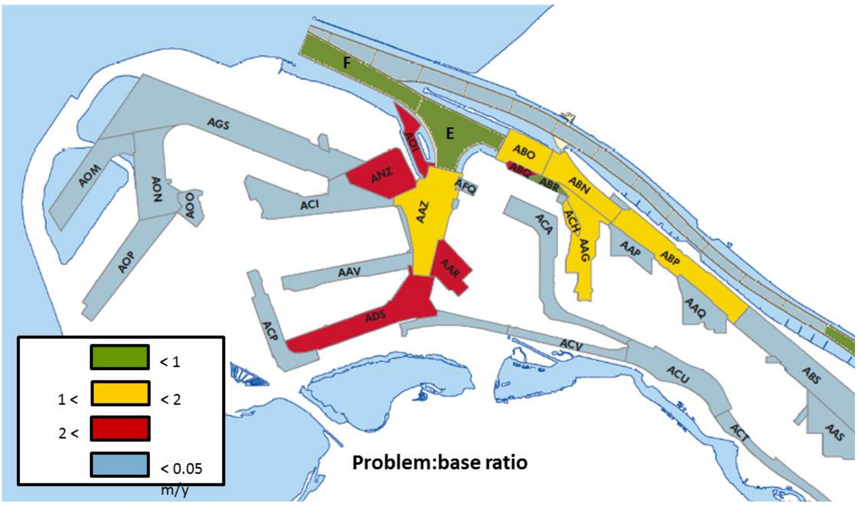

Figure 5.1: Development of maintenance dredging volumes within CaBe-system

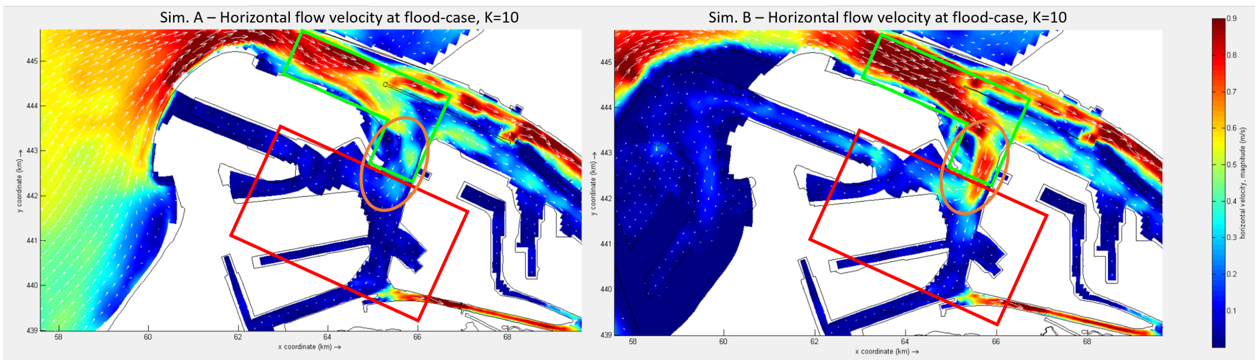

Figure 5.2: Results of plan overview of the flood-case horizontal flow velocities at the bottom (K=10) layer of Simulation A (left) and Simulation B (right) comparison to data analysis

The results of the hypothesis assessment describe that the consequences of the event, next to the correlated period of occurrence, also indicate a change of the hydrodynamic system that declares the redistribution of the sedimentation rates in accordance with the research analyses. Taking into account all research outcomes, the research hypothesis - *'The dominant factor responsible for the increase in maintenance dredging volume* *experienced by PoR is a change in local hydrodynamics by the construction of MV2'* - is accepted. It is concluded that the construction of MV2 is the dominant driving mechanism for the increase in maintenance dredging volume at PoR over the last decade. The conclusion is treated in more detail in Chapter 6, but is already taken into account regarding the recommendation of a reduction measure described in the following section.

5.2. Sediment trap

The recommendation done within this section is based on findings done during research and is in line with the research scope. The aim of this research is to describe a realistic reduction measure, relatively short-term applicable and that immediately affects the research problem. The research conclusion attributes the increase in maintenance dredging volume at PoR to a redistribution of sedimentation rates within CaBe-system, instead of to an increase of the sedimentation rates itself. For that reason the studied solution lies within a reduction of the maintenance dredging activity rather than a reduction of the maintenance dredging volume.

To start, a note that should be kept in mind is made. The increase in maintenance dredging volume at PoR is a consequence of the construction of MV2. As MV2 is of major importance to the development of PoR and its global competitive position, an easy solution such as closing MV2 off is not an option. Furthermore it should be understood that the construction of MV2 is an event of an extensive size. Together with MV1 it forms the largest and deepest harbour basin of PoR, visited and hence influenced by vessels of the largest size thinkable. In other words, MV is a very extensive and energetic harbour basin. A potential measure has to be of substantial size to influence a harbour basin of this size and robust enough to withstand an energetic environment like this. The result is a recommendation in the form of a sediment trap.

A sediment trap is a local deepening of the bed level of the harbour basin with the intention to induce sedimentation at that location. By the deepening of the bed level flow velocities decrease, which provides sediments with a smaller grain size to settle. By doing so, the sedimentation can be more concentrated at one area and at a more favorable location. A location can be more favorable regarding the maintenance dredging activity in the sense of sailing distance to the disposal location, higher accessibility for dredging vessels or a lower complexity (for example in the form of obstacles within the dredging section). In other words, a sediment trap affects the sedimentation rate distribution and does not specifically reduce the maintenance dredging volumes, but is an improvement to other aspects of the maintenance dredging activity. Advantages of a sediment trap are that it is relative short-term applicable, easy adjustable to the situation, can be constructed with equipment that is already used for the maintenance dredging and no significant (financial) risks are included.

The recommendation of a sediment trap is based on influencing the driving mechanism responsible for the redistribution of sedimentation rates by the construction of MV2, the increase of the horizontal flow velocities. The reasoning is done with use of the basic formula to calculate flow velocity: $v = Q/A$. Where in this case a reduction of Q (tidal discharge) is not realistic, the solution is searched in an increase of A (flow surface). The area of PoR is fully utilized and leaves no room to widen the geometry horizontally. The only option left is an increase of the depth, the result is a sediment trap. The most important parameters are the dimensions of the sediment trap. At first, the over depth of the sediment trap compared to the original depth determines the factor of decrease of the flow velocity. The width and length of the trap determine the effectiveness. Logically the flow pattern has to develop itself over the deviated depth. Once the velocity reaches a point where sediments with a smaller grain size are able to settle, the settling time should be taken into account. In both ways an increase of the length and width results in an increase of effectiveness of the sediment trap, the same takes into account regarding the depth.

As already mentioned in Section 3.1.2, sediment traps on a smaller scale have proven its effect at several other harbour basins of PoR (one at BL, two at PN, two at EW). In Table 5.1 the details and efficiency of the sediment traps are provided. Important note is that these harbour basins are located in a different environment, have an over depth of approximately 3 metres and a covered surface significant smaller than the sediment trap recommended for CaBe-system. Also, the sediment traps are sometimes used as temporary buffer location

[1] This means that the administrated value not only represents the volume of 'trapped' sediments but partly contains disposal volumes that are dredged later on (resulting in an overestimation of volume). Next to that the designed depth is not always maintained as it should be for a best interpretation of the effectiveness. An example of the location of two sediment traps is shown with use of PN in Figure 5.3.

Harbour basin	Dredging volume sediment trap(s)	Dredging volume entire basin	Volume ratio trap:basin	Surface sediment trap(s)	Surface entire basin	Surface ratio trap:basin
Unit	$[m^3/y]$	$[m^3/y]$	[-]	$[m^2]$	$[m^2]$ mln	[-]
BL	397k	1.600k	0.25	0.11 mln	6.13 mln	0.02
PN	326k	588k	0.55	0.17 mln	1.44 mln	0.12
EW	247k	537k	0.46	0.20 mln	5.38 mln	0.04

Table 5.1: Details of the efficiency of sediment traps at PoR. The volumes mentioned are averaged yearly volumes over 2005-2016 (problem and base period)

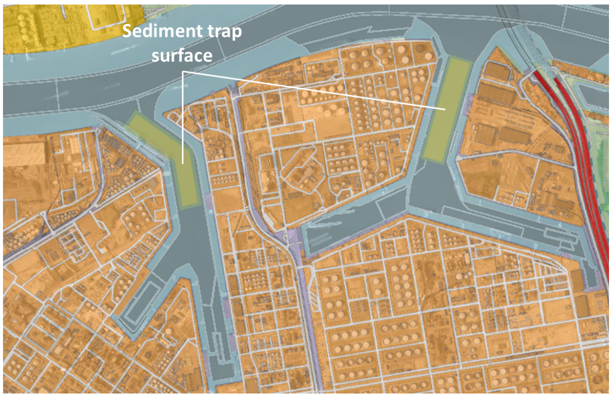

Figure 5.3: Location of the sediment traps at PN, depicted as yellow rectangles

5.3. Location

Apart from the dimension, the location of the sediment trap is decisive for the impact on the hydrodynamic system. A study to possible locations of a sediment trap to influence the redistribution of sedimentation rates within CaBe-system results in a recommendation for a sediment trap located in the front of CaBe-MV1. Another option studied was a trap located at CaBe-RWS, as this is the location where originally the sedimentation took place. Nevertheless, taking into account the flow velocities measured at CaBe-RWS the effectiveness of a sediment trap at that location is assessed not to be realistic. To reach the flow velocity where sediments were able to settle before, the sediment trap is required to have an over depth of up to 13 metres (based on measuring station Beerkanaal Monding). In addition, a high flow velocity needs a larger surface to form its flow profile to the deviating depth compared to low velocities. Based on these reasons a sediment trap located at CaBe-MV1 is assessed to be more effective.

Considering Figure 5.2 and the results following from the flow model simulations, an increase of flow velocities with a factor of up to 2.0 is measured at station 'Papegaaienbek Beerkanaal'. A rough calculation of the factor of decrease is done to describe the impact of a sediment trap to the horizontal flow velocity. If it is assumed that the horizontal flow velocity during flood (which is the main aspect regarding sedimentation rates) is concentrated over the bottom 15 metres, a sediment trap with an over depth of 5 metres (assumed to be reasonable as a large scale variant of the already existing sediment traps) results in a decrease of the flow velocity with a factor of 0.25. The rough calculation illustrates that a sediment trap is not able to bring back the hydrodynamics of the current situation (Figure 5.2 on the right) to the old situation (Figure 5.2 on the left). Hence, a sediment trap is expected to influence the sedimentation rates at CaBe-MV1, but only in a

[1]A location at which dredged material is disposed if for example a vessel or crane does not have the capability to transport it directly to the North Sea.

certain order of magnitude.

The recommended location of the sediment trap is in the front of CaBe-MV1. The flow velocities at MV1 are relative low and closer to the critical velocity. This way a broader range of suspended particles are subject to the impact of the measure and further intrusion of MV1 is prevented. The sediment trap is located just in front of the connection between CaBe-MV1 and CaBe-RWS, where the flow velocities are already relatively low by the width of the harbour basin. The recommended area location is presented with use of Figure 5.4. It must be clearly understood that this is just a rough sketch and the depicted surface area is an estimation, not based on calculations. Logically, the result of this location regarding the sailing distance is not as profitable as it would have been at CaBe-RWS. The profit is mainly found in the advantages of the area the sedimentation is concentrated. MV contains several busy terminals occupied by large vessels for a long period of time. This way a higher efficiency and lower loss of time is obtained as the location is better and more frequent accessible for the dredging vessels.

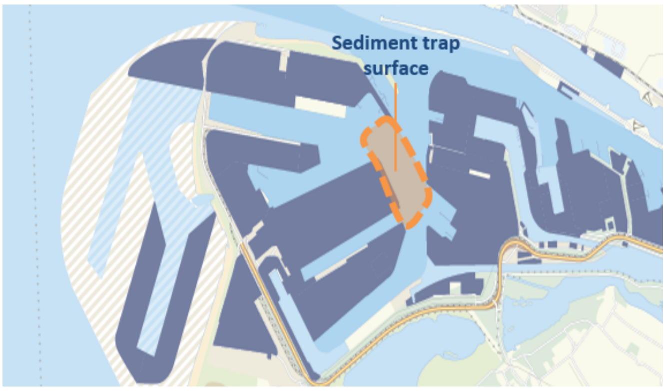

Figure 5.4: Recommended area regarding the location of a sediment trap at CaBe-MV1

Currently research to different uses of sediment traps is going on. An interesting research related to the recommendation described above is done by Kiricheck et al. [2018], where fluid mud is produced by water injection dredging in the Port of Rotterdam. By use of water injection dredging, the top layers of the sediment around a sediment trap can be liquefied and mobilized in a way that the mud flow is directed into a sediment trap. Additionally, research to the effectiveness and added value of sediment traps in the port area regarding the maintenance dredging activity is done.

To close the chapter, some last points of attention for a right reading of the above are clarified. A recommendation in the form of a sediment trap is the most sufficient solution regarding the outcome of this research. Reduction measures of a different type can not be excluded. The recommendation presented above is just a rough sketch that arises from research with the aim to describe the possibilities of a measure of this kind. Further research to the exact location, dimensions and efficiency is required before proceeding to any action. Finally it must be said that the research problem is one of the consequences of the construction of MV2, and hence partly have to accepted as well.

6

Conclusion and recommendations

The last step of the final research phase is presented in this chapter. For this research, two research objectives are introduced in Chapter 1: 1) identify the main mechanisms for the increased maintenance dredging volume at PoR over the problem period and relate this increase to historic events; 2) identify a measures to reduce the maintenance dredging activity; Together both objectives provide an answer to the main research question:

What is the dominant mechanism leading to the increase in maintenance dredging volumes at the Port of Rotterdam in the last decade and which measure could potentially reduce the maintenance dredging activity in the Maasvlakte-area?

In Chapter 5 the answer to both research objectives is provided. The selected hypothesis is accepted and the research conclusion is defined. A further elaboration of the conclusion is provided in Section 6.1. Subsequently the research results are subject to a discussion in Section 6.2. Finally the research closes of with recommendations for further research in Section 6.3.

6.1. Conclusion

The several research phases result in the definition of the research conclusion. The main findings done during research that lead to the research conclusion are outlined below.

'The dominant mechanism leading to the increase in maintenance dredging volumes at the Port of Rotterdam is a change in local hydrodynamics by the construction of Maasvlakte II, resulting in a redistribution of the sedimentation rates within CaBe-system.'

- Based on an analysis of the administrated maintenance dredging volumes of PoR, the problem of an increase at the sections of PoR is concentrated at MV1;
- With use of the administrated maintenance dredging data of RWS, it is concluded that not an increase of sedimentation over the entire port area is responsible for the research problem, but rather a redistribution of the sedimentation rates from CaBe-RWS to CaBe-MV1 is;
- Based on the correlation of time and potential impact on the hydrodynamics of the water system, the event 'Construction of MV2' is selected and subject to an assessment with use of hydrodynamic flow model simulations;
- With use of the flow model simulations the impact of the event on the hydrodynamic conditions in CaBe-system is measured, in particular in the form a strong increase of the horizontal flow velocities over CaBe-RWS, mainly directed to CaBe-MV1.

- The results of the assessment correspond with the results of the research analyses. Hence the hypothesis - *'The dominant factor responsible for the increase in maintenance dredging volume experienced by PoR is a change in local hydrodynamics by the construction of MV2'* - is accepted;
- Based on the research outcome, a reduction measure in the form of a sediment trap in the front of MV1 is recommended.

6.2. Discussion

Below the data used for research and possible deviations in the outcome are discussed to ensure a good interpretation of the research results.

- The base of this research is the maintenance dredging volume data administrated by PoR and RWS. On the smallest detail these volumes are described to dredging sections. The research results in a description of the problem as a shift of the sedimentation rate concentration over dredging sections. Dredging sections are still rough and hence do not provide insight into the exact pattern of sedimentation.
- As explained, maintenance dredging volumes do not directly correspond to sedimentation rates and are influenced by several other factors. The impact of the dredging strategy of the asset managers is left untreated due to a lack of essential information on the subject. It is expected that the dredging strategy is able to explain some remarkable findings where no logical answer to is provided during research. Examples that are of interest for this research are the strong fluctuating yearly maintenance dredging volumes of RWS and the sudden decrease of maintenance dredging volumes since 2007 at the dredging sections of RWS.
- The research conclusion states that the construction of MV2 is the dominant factor responsible for the increase in maintenance dredging volume by PoR. This does not mean that the problem is fully attributable to the construction of MV2. The water system within PoR forms a very large and complex hydrodynamic system, influenced by a broad range of factors. Every event has in its own extent an influence on the water system and hence on the sedimentation rates. Due to the complexity of the system there will always be an uncertainty when relating a change of dredging volumes to something as an event.
- There are construction works continuously going on at MV2 since 2009, including the entire problem period. Construction works such as land reclamation (which is one of the main activities regarding MV2) have proven to work as a catalyst on sedimentation rates, as extra fines are supplied to the water system. It is expected that the construction works at MV2 have resulted in an additional increase of the maintenance dredging volumes analysed.
- It should be taken into account that MV2 is still under construction and new terminals are currently being realised. This means that the wet surface and hence the tidal filling volume of MV2 are subject to a change, in this case in the form of a decrease. A visualization is provided with use of Figure B.2 of the Appendix. A decrease of the tidal filling volume would logically reduce the change of sedimentation rates observed over the last couple of years.

A last point of attention elaborated in more detail is the substantial increase of the horizontal flow velocity resulting from the hydrodynamic flow model simulations. A maximum increase with a factor of 2.0 is measured in the connection between CaBe-RWS and CaBe-MV1. It is expected that this factor of 2.0 can not fully be described to the increase of tidal discharge in combination with a strengthened estuarine circulation described in Chapter 4. Other factors that are not further studied might play a role. The report uses the ebb- and flood-case of one specific tidal cycle, the two most extreme moments in time regarding flow velocity. A more accurate calculation would result from integrating the horizontal flow velocity over time and comparing the averages. Unfortunately this option is not included in QuickPlot. Additionally, Quickplot only provides the option to draw graphs of standard implemented measuring stations. Multiple measuring stations over the connection from CaBe-RWS to CaBe-MV1 would provide a better understanding of the actual behaviour. It is expected that the increase of tidal discharge focuses at the lower layers, is concentrated in the middle of the transection and less noticeable at the area more close to the waterway geometry.

6.3. Recommendations

Based on the research conclusion and the research discussion, the recommendations for further research are outlined below.

- Further research to the dredging strategy of both asset managers and possible changes over the last decade is strongly recommended. More insight into the dredging strategies provides a better understanding of the development of the maintenance dredging volumes. Deviating values that result from maintenance dredging strategy can be filtered out of the data resulting in a clear view on the sedimentation rate development due to physical processes only.
- A detailed study to the design and effectiveness of a sediment trap at MV1 is required. This research only presents a rough sketch to describe the method and possibilities a sediment trap offers. Further research to the exact location, surface, maintained depth, impact on the sedimentation processes and approach of maintenance is required. Besides, the recommended measure results from the research outcome as it is a method to reduce the horizontal flow velocities. This does not mean that it is the only possible measure to reduce the maintenance dredging activity and further research to reduction measures of a different kind should not be excluded.
- Insight into the exact pattern of sedimentation would be a significant improvement to the research problem understanding. For that reason a detailed study to the sedimentation pattern within CaBe-system is recommended. Now the location where the problem is concentrated is known, use could be made of surveying maps (used to determine if maintenance dredging is required) that describe the bottom levels in high detail. This way the sedimentation pattern of the current situation can be studied and compared to the pattern before the construction of MV2.
- A factor not taken into account for this research is the composition of the dredged material. The material dredged at CaBe-RWS originally consisted of more coarse particles. The problem is described to an increase of horizontal flow velocities at CaBe-RWS, resulting in the transport of sediments that before were able to settle at this location to CaBe-MV1. A study to the bed material at both locations is recommended. Data on the bed material is available, as every year a research to the bed composition of all dredging sections is done to be assessed on possible contamination. A study to the development of bed material over the problem period might support the findings done in this research.
- As describe in detail in the section above, several other aspects are expected to be of influence on the measured maximum factor of increase of the horizontal flow velocity of 2.0. A detailed study to declare this outcome is recommended.
- The final recommendation regards the awareness of the consequences an intervention to the port might have on the hydrodynamic conditions. As resulted from this research a (relatively small) change to the tidal filling volume can induce a significant change of the hydrodynamic conditions of the system resulting in a undesired situation, in this case in the form of an increase to the maintenance dredging volume. Hence (if not the case yet) it is recommended to deeply study the impact future port development has on the hydrodynamic environment to be aware of otherwise unforeseen consequences.

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A
Maintenance dredging maps

An overview of the harbour basins is provided with use of A.1.

A.1. Map 1

The first map is an overview of all dredging sections and includes the codes of the dredging sections under control of PoR. The pale yellow coloured sections are the sections under control of RWS.
Details of the sections covered by the harbour basins are given below:

MV: AAT - AAV - AAZ – AMU – ACI – ACP – ACW – ADS – AGS – AOI

MV2: AOM – AON – AOO – AOP

EUP: AAP – AAQ - AAR AAS – AAG – ABL – ABN – ABO - ABQ – ABR – ABP – ABS – ABT – ABX – ACA – ACB – ACH – ACS – ACT – ACT – ACU – ACV – ADK – ADW – AES – AFG – AFQ – AGO

BL: AAF – AAL – AAM – AAN – AAO – ABF – ABG – ABH – AOZ – ABI – ABJ – ABK – ABV – ACN – ACM – ACQ – ACR – ACX – ADZ – AFO - AFR - AJE

PN: AAB - AAC – AAD – AAE – AAH - AAI - AAJ – AAK – AOT – ATE - AGJ

FH: ACZ – ADB – ADE – ADG – ADR - AFE

EW: ACC – ACE – ADD – ADQ – ADT – AEG – AEJ – AEM – AEL – AEP – AFM – AFH – ACY – AGN – AGL – AMD – AMF – AMG – AMH – AMI – AMJ – AMK – AML – AMM – AMN – AGK – AGM – AMO – AME – AMC – AOE - AEN

SH: AGQ – AMT – ADC – ABZ – AIY – ANC – ADN – AGY – ACK – ADV – ADX – ADH – AEB – AEC – ANB – AFD - ADJ

A.2. Map 2

Map 2 provides an overview of the locations maintenance dredging is concentrated.

A.3. Map 3

This map provides an overview of the maintenance dredging development by comparing the peak period to the base period. This way the to get insight into where the problem as experienced by PoR is concentrated. The colours represent the peak:base ratio in the order of magnitude mentioned in table. The grey areas are the dredging sections with a peak period average maintenance dredging of below 0.05 m/y (green in map 2) and are not taken into account considering the problem.

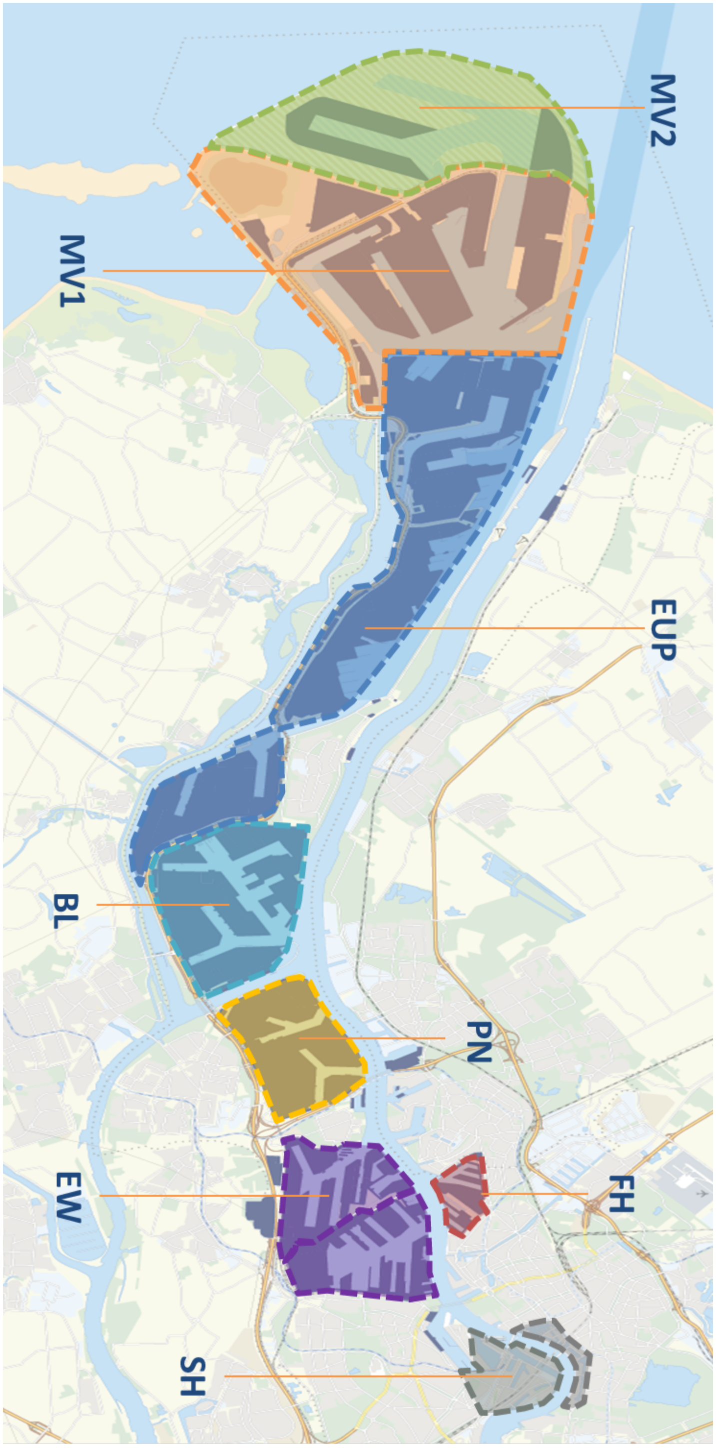


Figure A.1: Overview of harbour basins Maasvlakte II (MV2), Maasvlakte I (MV1), Europoort (EUP), Botlek (BL), Pernis (PN), Eem- Waalhaven (EW), Fruithavens (FH), Stadhavens (SH)

Figure A.2: Overview dredging section names

Figure A.3: Yearly maintenance dredging activity problem period

Figure A.4: Maintenance dredging development Problem:Base

B

Internal events

A brief description of all internal events is given below. An overview of the locations is found in Figure B.1.

Figure B.1: Overview plan of internal events taken into account

B.1. Maasvlakte 2 (2008 - 2013)

Maasvlakte 2 is the western extension of the PoR in the North Sea. A total surface area of 2,000 hectares is created by spraying on sand off the coast. The land reclamation started in the end of 2008. The sand has come from sand extraction sites in the North Sea and by cutting through of Yangtzehaven. In the end of 2011 the Yangtzedam, separating MV1 and 2 during construction, is cut through making MV2 accessible for vessels. Within MV2 construction works are currently still ongoing as new harbour terminals are created. The future layout is shown with use of Figure B.2.

Figure B.2: Map of the current layout of MV2 (left) and future layout (right)

B.2. GATE terminal (2011)

The Gate terminal is the LNG import terminal in Rotterdam, located on the Maasvlakte near the port entrance. The site that was selected for this purpose is located in the north western part of Maasvlakte 1 and had to be reclaimed from the harbour basin in a former sand borrow pit.

The site was constructed in 2008 by depositing sand dredged from the former adjacent new Yangtze harbour. To consolidate (pre-load) the underground properly, an additional 10-metres of sand was placed on the future storage tank locations. The construction of the site itself started in 2008 and was ready for commercial operations in September 2011. The berths have a MD of -14.5m NAP, which is low compared to the surrounding -23.61m NAP

B.3. Sand Engine (2011)

Around the world, sand nourishments are applied as mitigation technique to increase beach width for recreation or coastal safety. For projects with a high frequency (every several years) and a large nourishment volume, it is questionable whether it has no detrimental effect on the fauna and if a more regional approach is not a better option.

An approach like that consists of a larger volume of sand placed at a single location with the intention to feed adjacent coast by redistribution in along and cross-shore direction. In this light a mega-scale distribution with the size of approximately 17 million m3 in an area of 2,5 km (along shore) by 1 km (cross shore) called the Sand Engine was implemented between the harbour entrances of Rotterdam and Scheveningen. The construction took place between March and November 2011 and its development is monitored intensively for research purposes.

B.4. Quay 8 (2014)

The construction of quay 8 in the Botlek harbour. The quay is located in the inner river bend between 1e and 2e petroleumhaven and its berths have a depth of -15.15 m NAP.

B.5. Doorn van Botlek (2014)

The Doorn van Botlek is an underwater dam at the entrance of the Botlek harbour, a very busy shipping area. By removing of the Doorn the MD (maintenance depth) at that location increased from -5.60 metres to -14.50 metres NAP. The construction started in August 2014. With the removal the accessibility of Botlek improved in particular for vessels with a high draft. In the new situation the effort for entering the harbour basin is made more easy and shipping more safe.

B.6. Berths Calandkanaal (2015)

At the northern edge of the Calandkanaal, a new function is assigned assigned to three berths. With this new function an increase of the MD is required. To realise the new berths, a volume of approximately 600.000m3 is dredged.

Maintenance dredging prognoses due to event: Because of the increase of MD it is expected that the berths will experience higher siltation rates.

B.7. Widening of Breeddiep (2016)

Breeddiep, the connecting channel between Calandkanaal and Nieuwe Waterweg which is an important route for inland shipping, has been expanded from 75 to 350 metres. The widening meets the demand of inland shipping for increased traffic capacity from and to the Maasvlakte.

C

Data analysis results

Note: The values plotted above the years are the cumulative values at the end of that year (example: 2016 should be read as 31 Dec 20016).

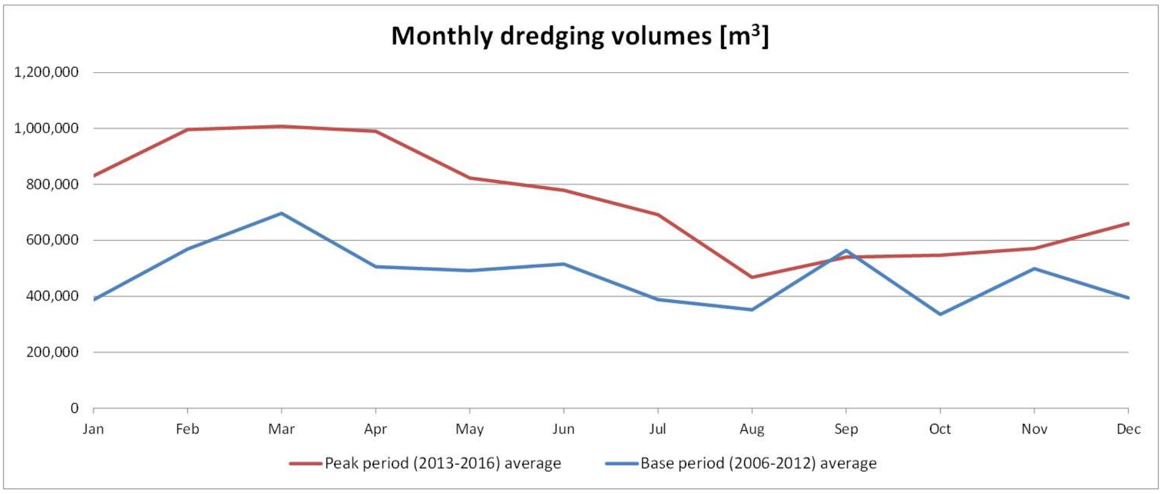


Figure C.1: Monthly maintenance dredging volumes of sections under control of the PoR. Note is made that the first step of analysis takes into account 2006-2012 as the problem period (instead of 2005-2012) due to the absence of data on some harbours basins in 2005

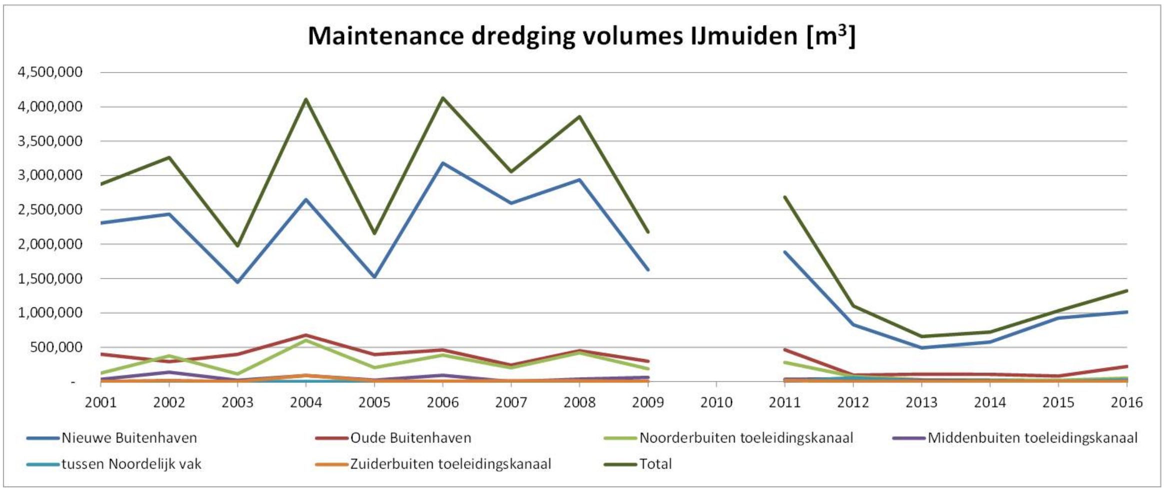


Figure C.2: Maintenance dredging activity of dredging sections within Port of IJmuiden (no data on 2010 is provided)

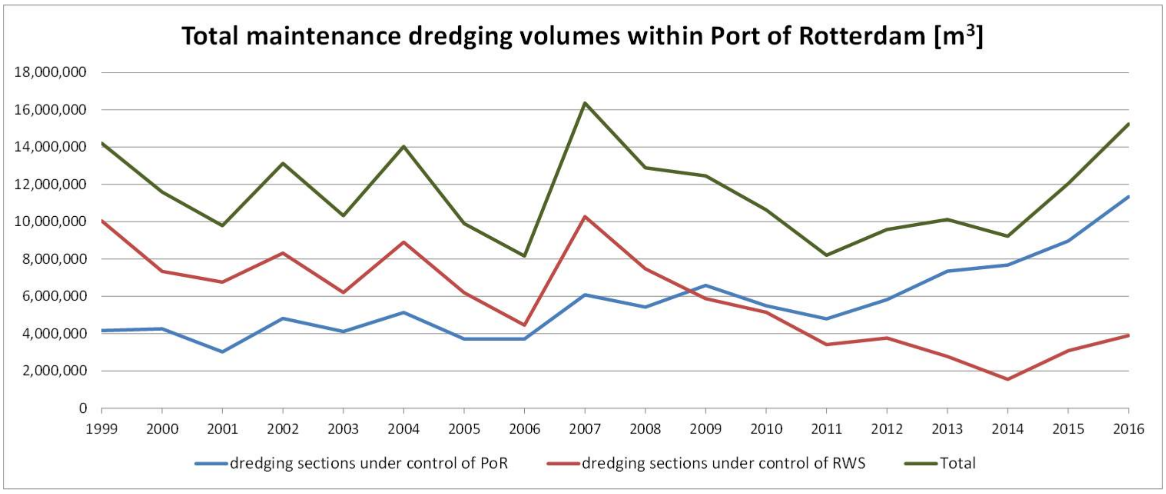


Figure C.3: Total maintenance dredging volumes within Rotterdam of both operators, PoR and RWS

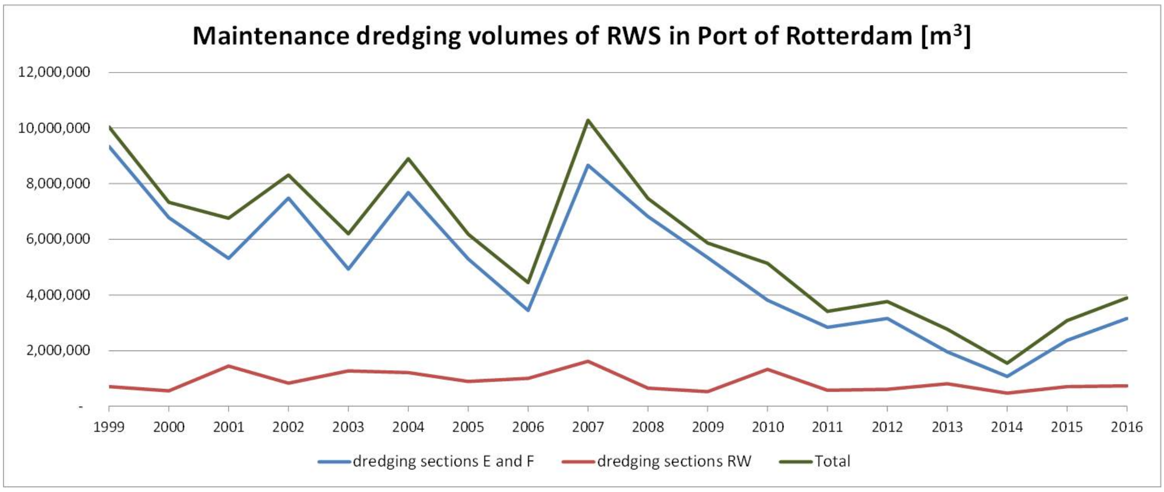


Figure C.4: Maintenance dredging activity of RWS in Rotterdam

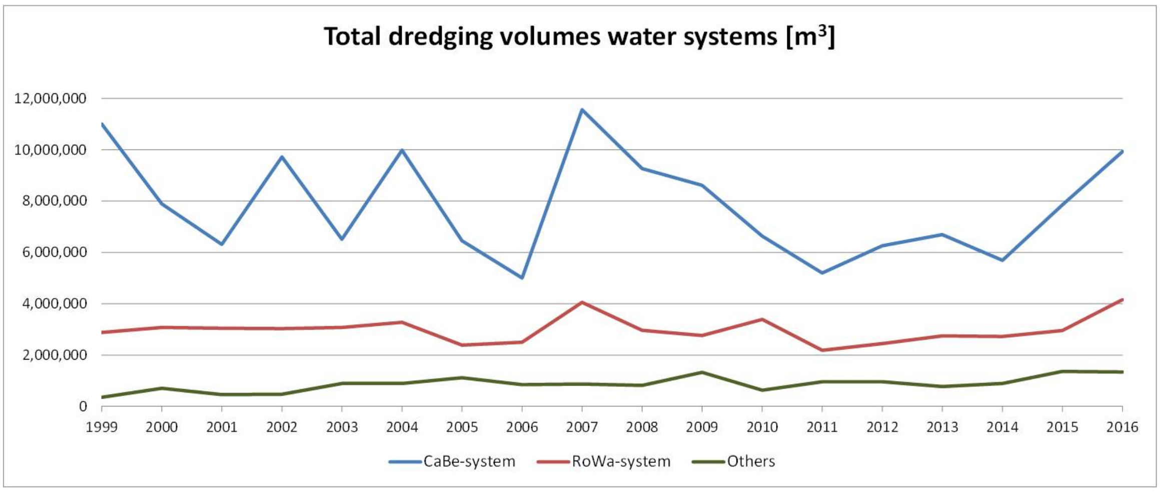


Figure C.5: Areas within CaBe-system including illustration of shift of sedimentation rates

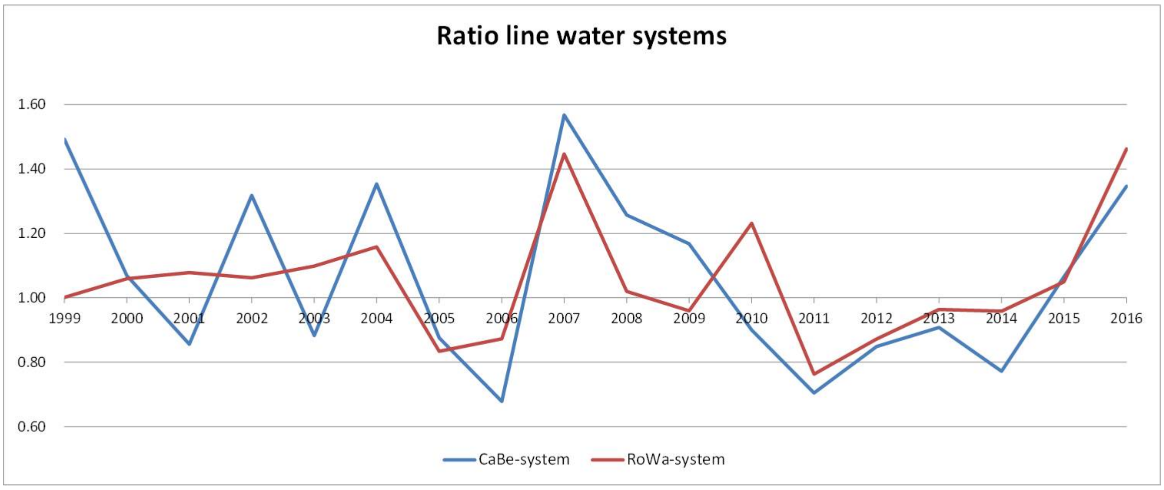


Figure C.6: Ratio lines of both CaBe and RoWa system

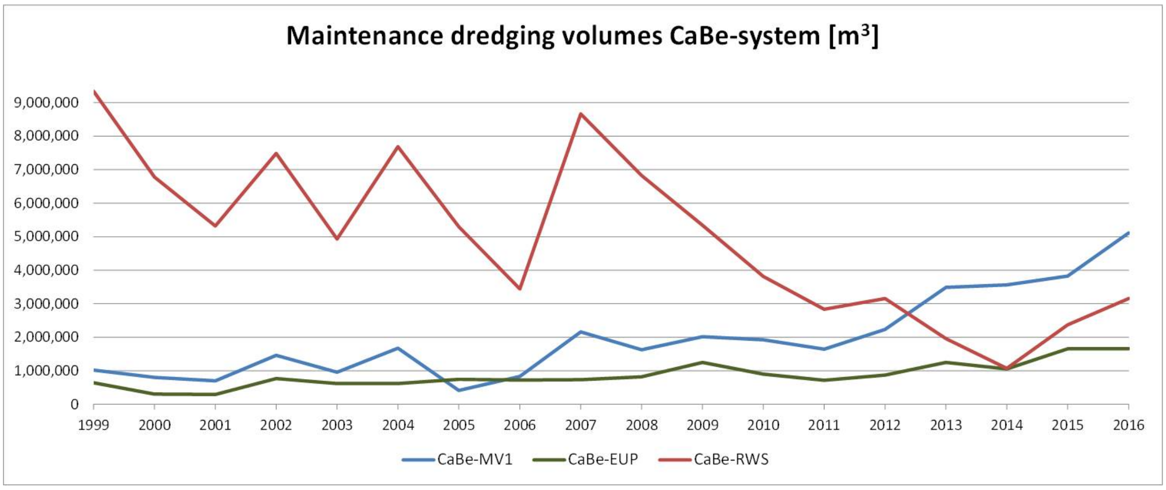


Figure C.7: Areas within CaBe-system including illustration of shift of sedimentation rates

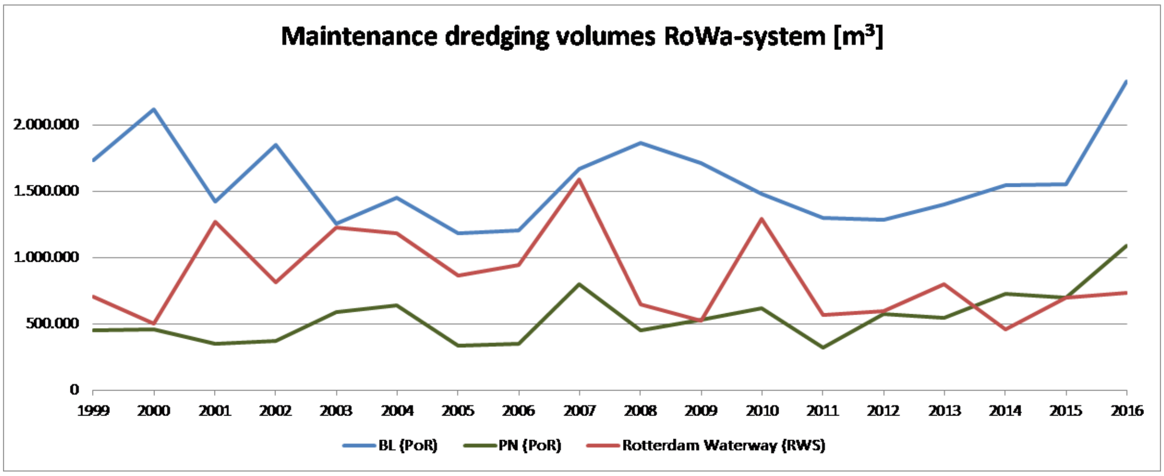


Figure C.8: Areas within RoWa-system to illustrate possible shift of sedimentation rates

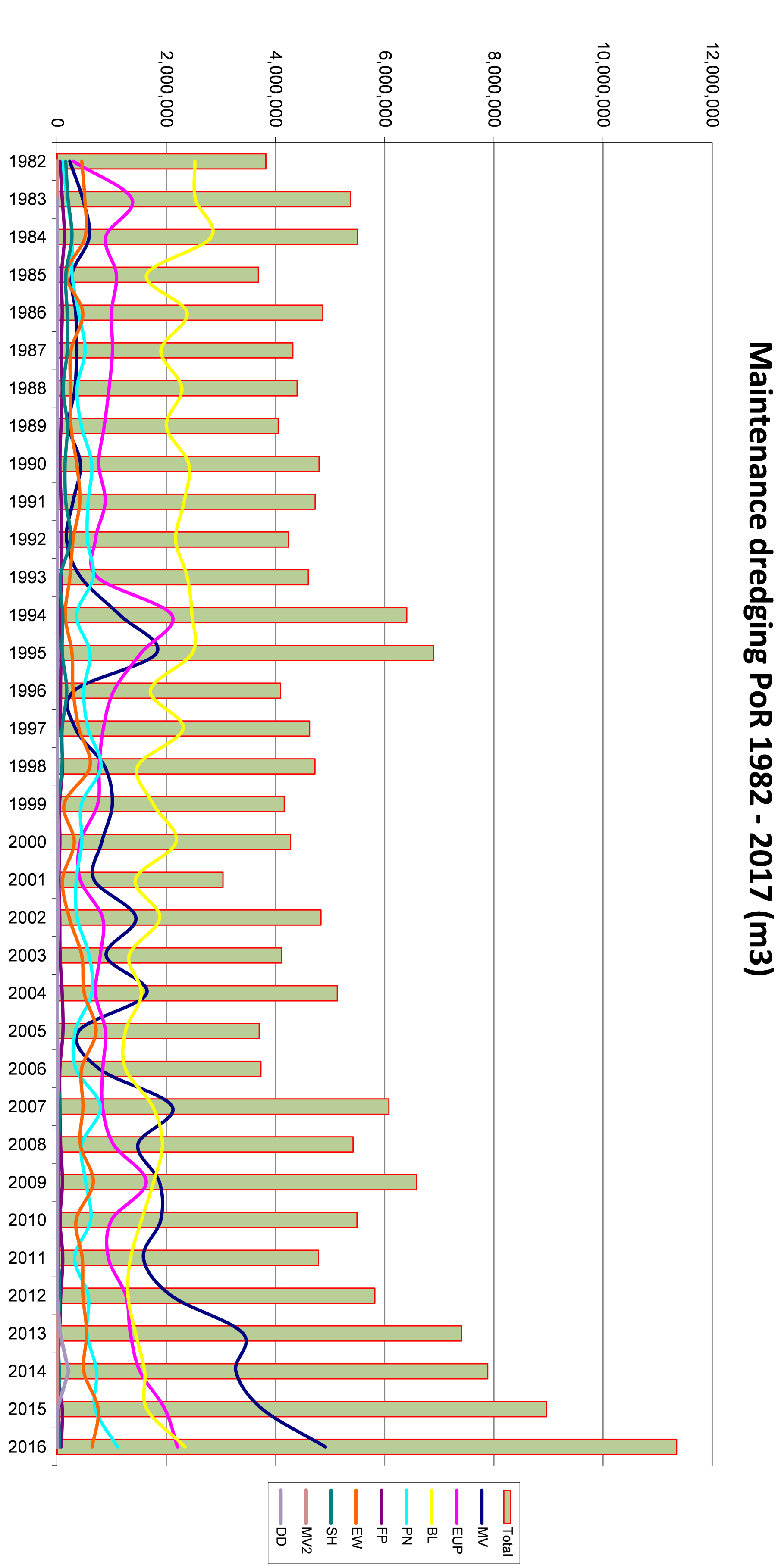


Figure C.9: Maintenance dredging volumes PoR

D
Correlation event and data analysis

Below the main graphs of the combination of the outcome of the event and data analysis are presented. The locations of the areas are found in Appendix A. The locations of the internal events are found in Appendix B.

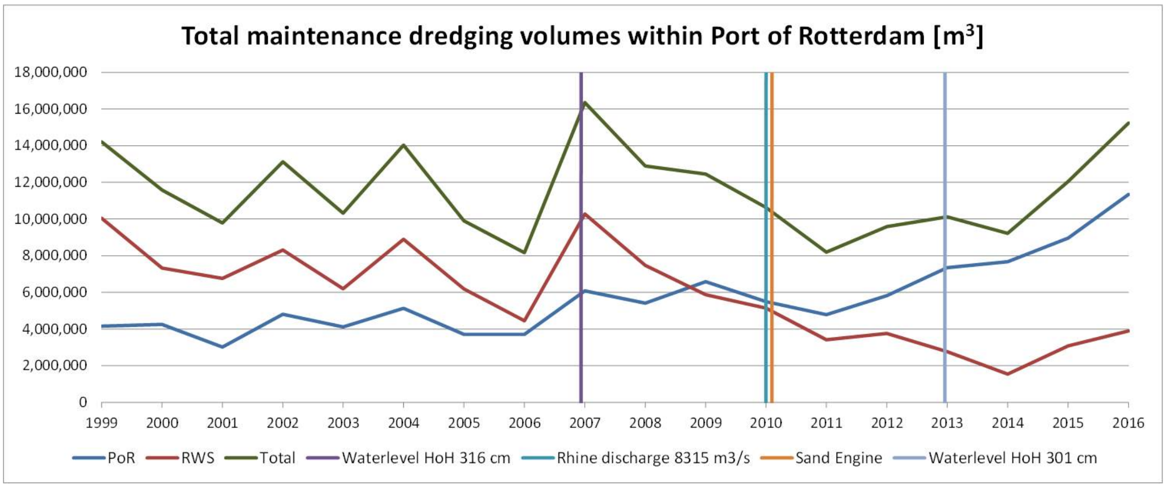


Figure D.1: Maintenance dredging activity at entire PoR area, including event B and the main external events

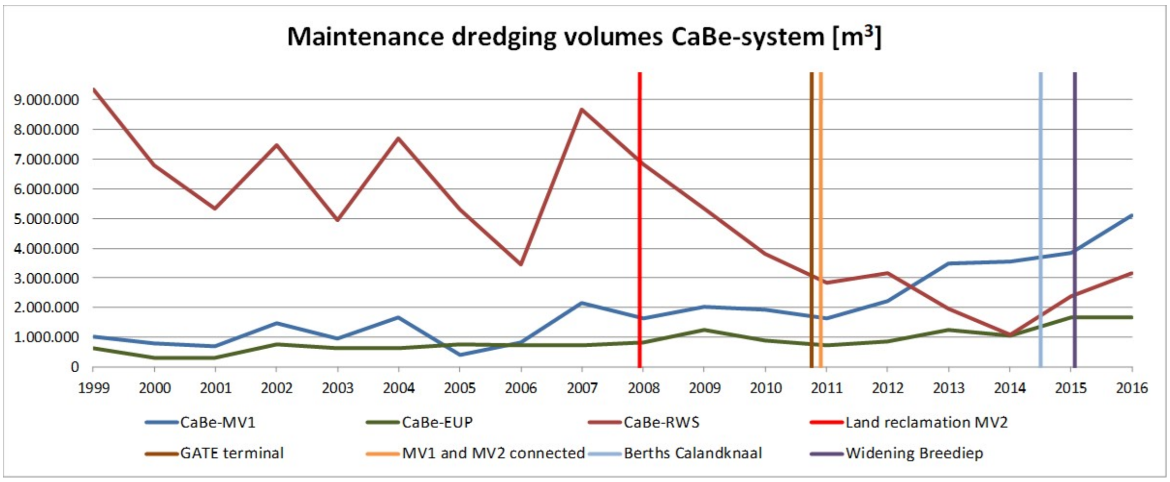


Figure D.2: Maintenance dredging activity at CaBe-system, including the events A, C, D, G and H

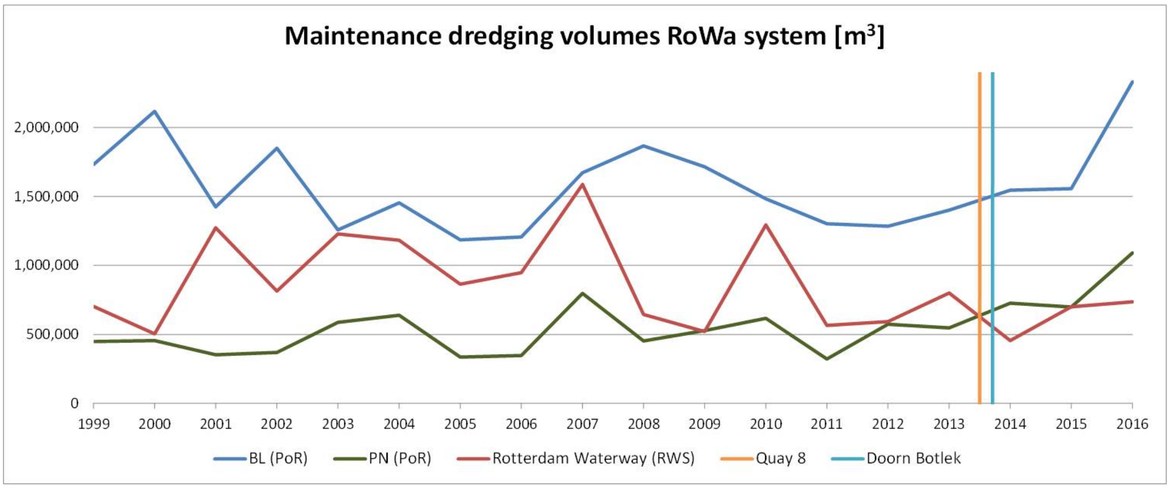


Figure D.3: Maintenance dredging activity at RoWa-system, including the events E and F

E

Run-up time test

To run a hydraulic flow model, input in the form of boundary and initial conditions are required. To ensure a representative model of the actual situation, a certain run-up time is required. The run-up time is the time a model needs to correct inaccuracies of the initial conditions and flattens these out. The required run-up time depends on the accuracy of the initial conditions in combination with the environment. Logically a simulation with accurate initial conditions requires a relative short run-up time. The same can be said about a high energetic environments. For example a harbour basin subject to high external forces (tide or discharge) will sooner reach its natural state (not an equilibrium as it variates over the tidal cycle) compared to a basin located in more sheltered area subject to less impact of the hydrodynamics. Regarding the parameters subject to an analysis during the hypothesis assessment, in particular salinity tend to have a relative long run-up time.

The simulations used for this research take into account initial conditions of an operational flow model of the current situation (thus including MV2). This means that if inaccuracies due to a short of run-up time are present, they would best be visible in Simulation A (old MV1 layout). For that reason all figures shown in this appendix concern Simulation A.

To assess if the period used is not subject to inaccuracies due to run-up, an additional simulation is done that extents the simulated period to 14 February. Results from the past turned out that the run-up period used for Simulation A and B (3 weeks) in case of this specific model under normal circumstances is more than enough for all parameters. To use the extended simulation to calibrate the simulations used for reporting, the salinity of the layer K=1 (dotted line) and K=10 (full line) of measuring stations located at the outer ends of the area of interest are plotted in the Figures E.2, E.3 and E.4. In blue the used simulation is shown, in red the extension for verification). Even though only the graphs since 15 January are plotted, the simulation started at 1 January, which corresponds with run-up time of three weeks used for this research.

The 21th of January, assessed in this appendix, is assessed to be representative for the actual situation and not to have inaccuracies due to run-up. This assumption is done based on the graphs, where no deviating values of the salinity profile of the measuring station at the boundaries are observed. Locations more seaward showed similar results and are assumed to have an even shorter run-up time because of the higher energetic sea environment it is subject to. On top of that the daily trends over the assessed period are comparable to each other and no deviations occur (which was expected in case of run-up errors). The tidal variating trend due to spring and neap tide show a little bump in the begin period (14-16 January) that might be a result of spin-up, but follow since approximately the 18th of January clearly the long term trend of the system.

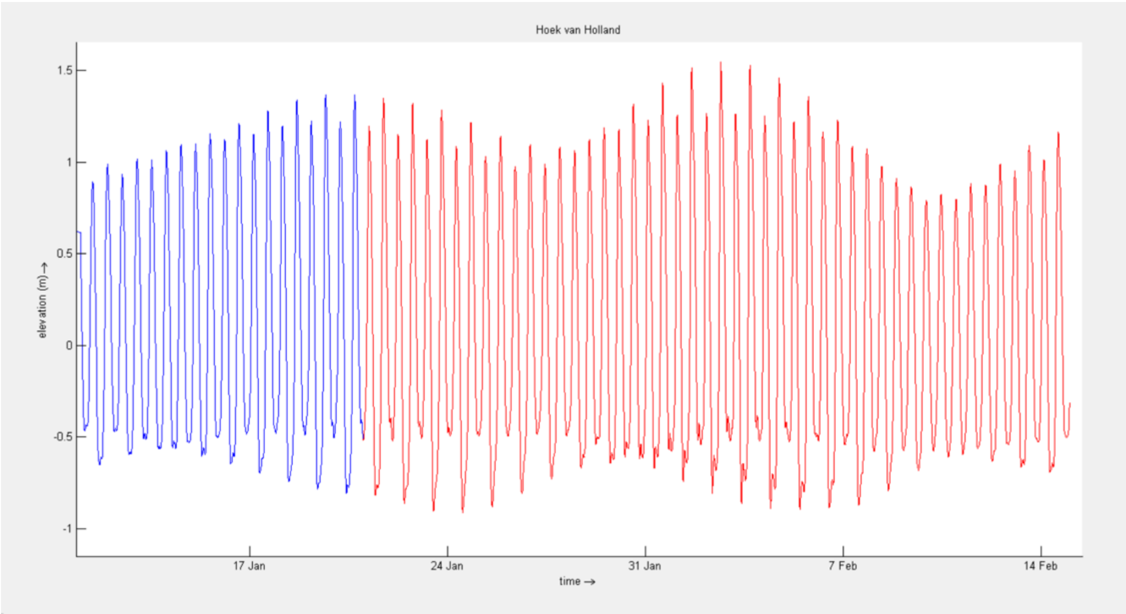


Figure E.1: Tide of the simulation at Hook of Holland

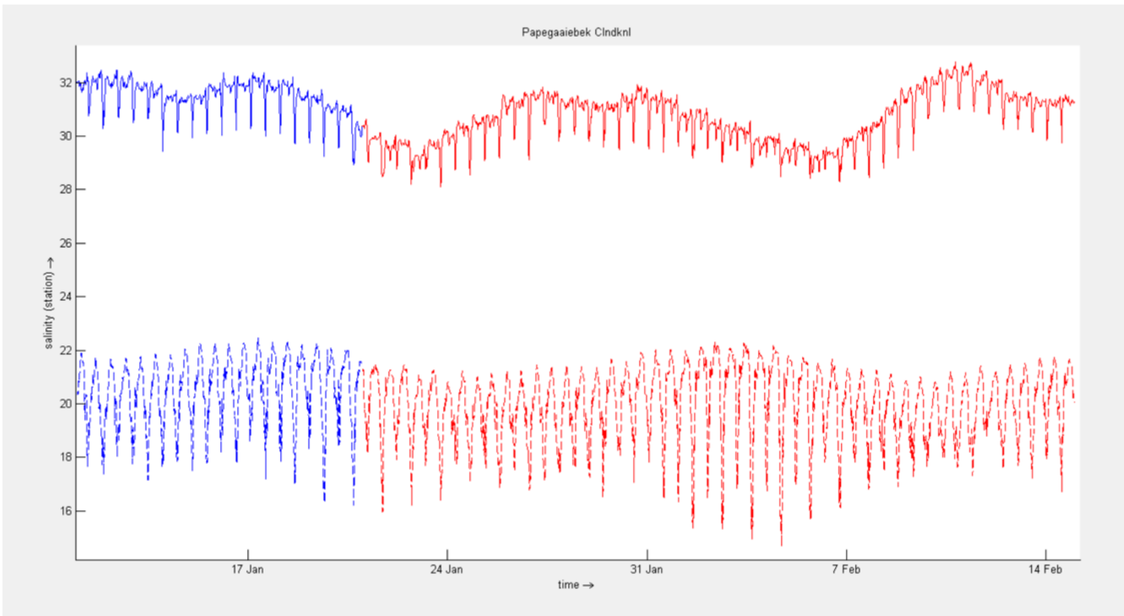


Figure E.2: Salinity over simulation of K=10 (full line0 and K=1 (dashed line) at 'Papegaaienbek Calandkanaal'

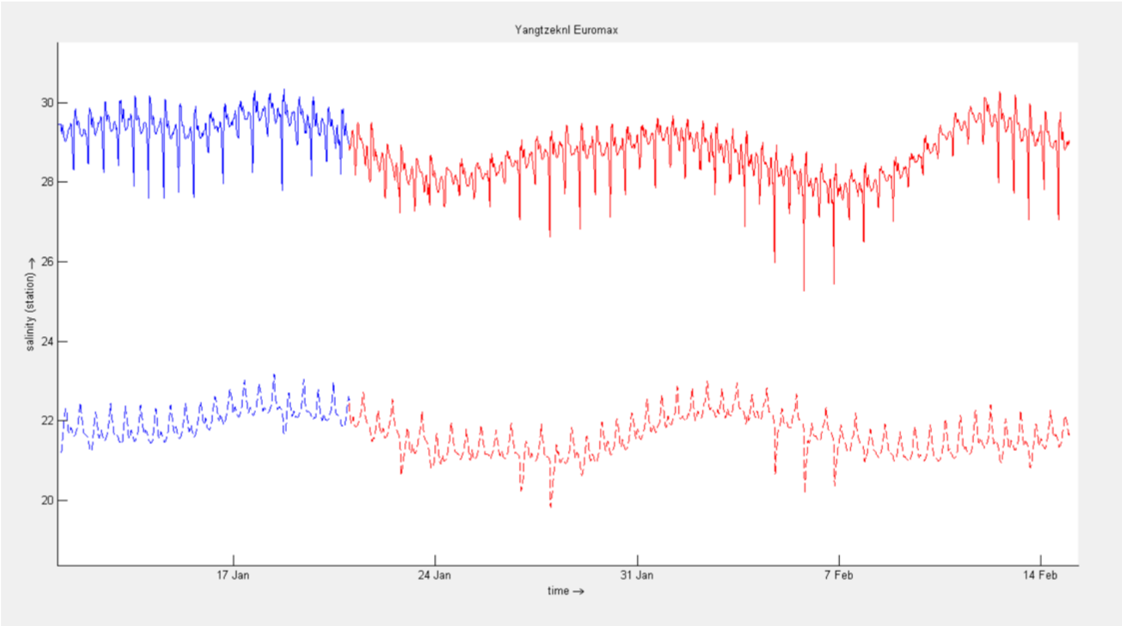


Figure E.3: Salinity over simulation of K=10 (full line0 and K=1 (dashed line) at 'Yangtzekanaal Euromax'

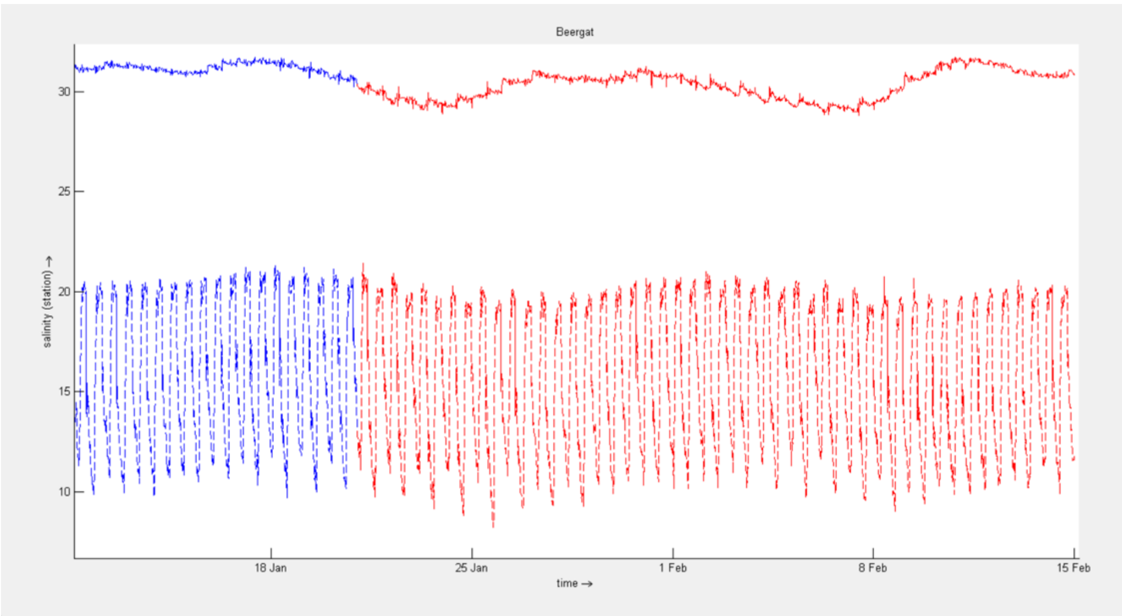


Figure E.4: Salinity over simulation of K=10 (full line0 and K=1 (dashed line) at 'Beergat'

F
Hypothesis assessment results

This appendix outlines all the figures that include results of the hypothesis assessment. The figures are categorized with use of the section headers. Details of the figure are described within the caption. The same figures (in case of added value) of Simulation A (left) and Simulation B (right) are presented next to each other.

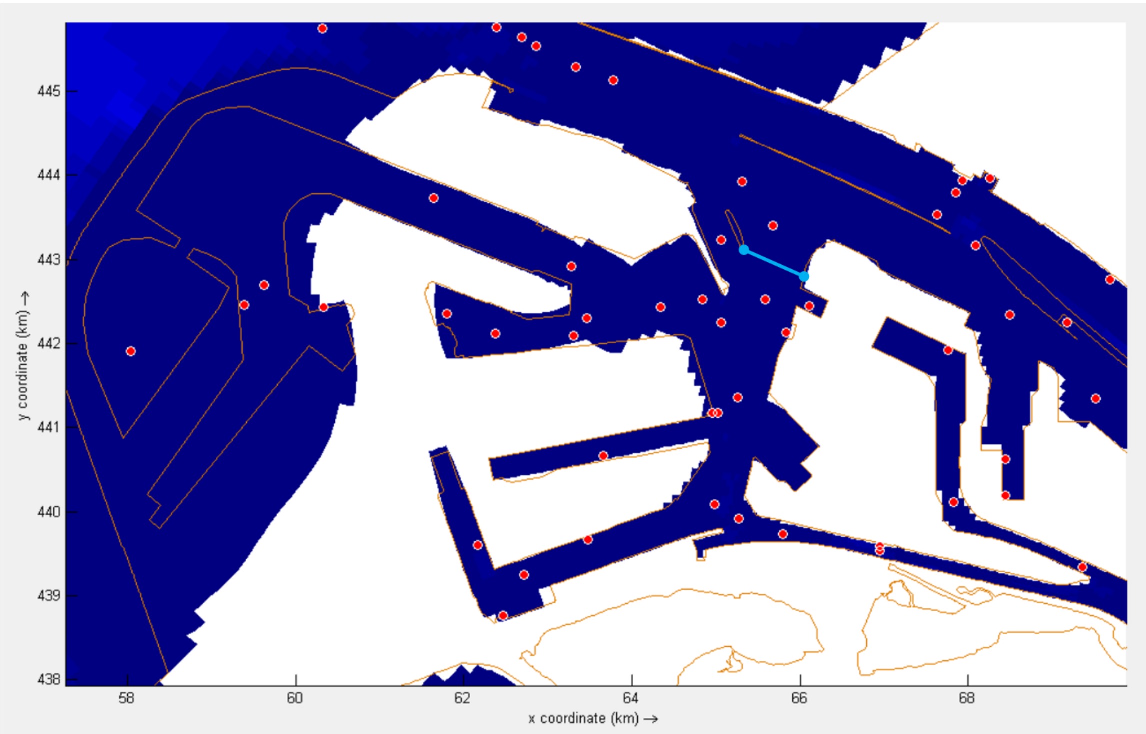


Figure F.1: Measuring stations within QuickPlot that are used for analysis. In blue the transection used for the tidal discharge calculation

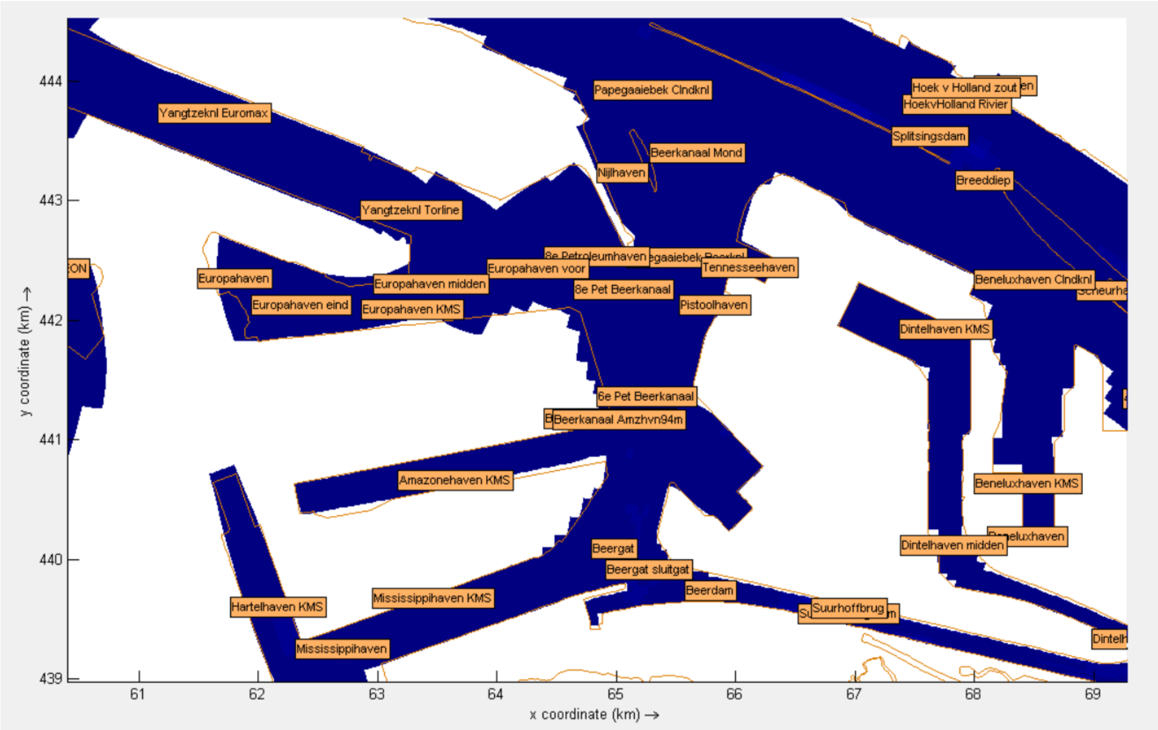


Figure F.2: Names of the measuring station used for reporting

F.1. Water level

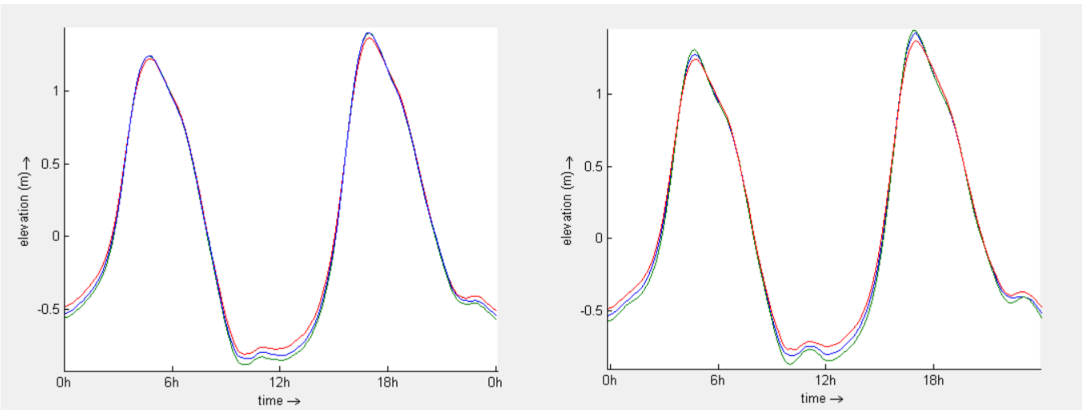


Figure F.3: Water level plotted over time at HoH (red), Beergat (blue), Yangtzekanaal Euromax (green)

F.2. Salinity

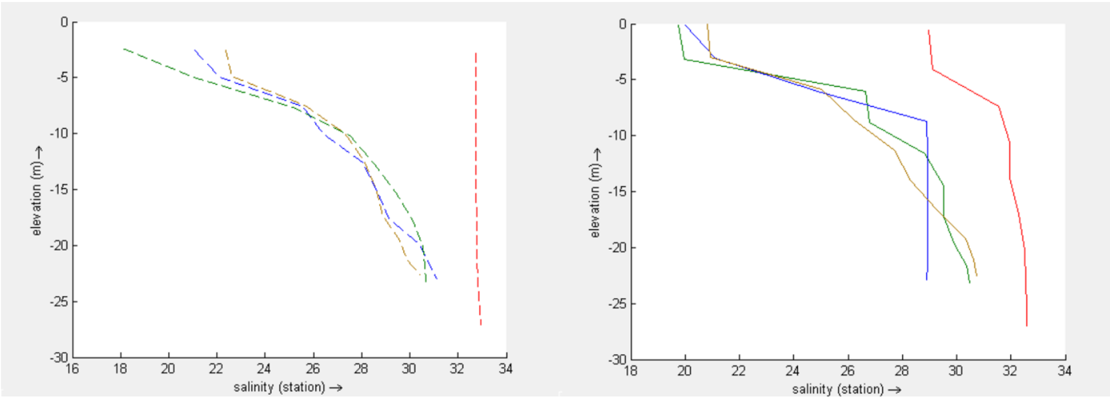


Figure F.4: Salinity profiles over depth at low-tide (dashed line) and high-tide (solid-line) of the measuring stations Maas-C Boei (red), Beerkanaal Monding (blue), Beneluxhaven Calandkanaal (brown) and 6e Petroleumhaven (green)

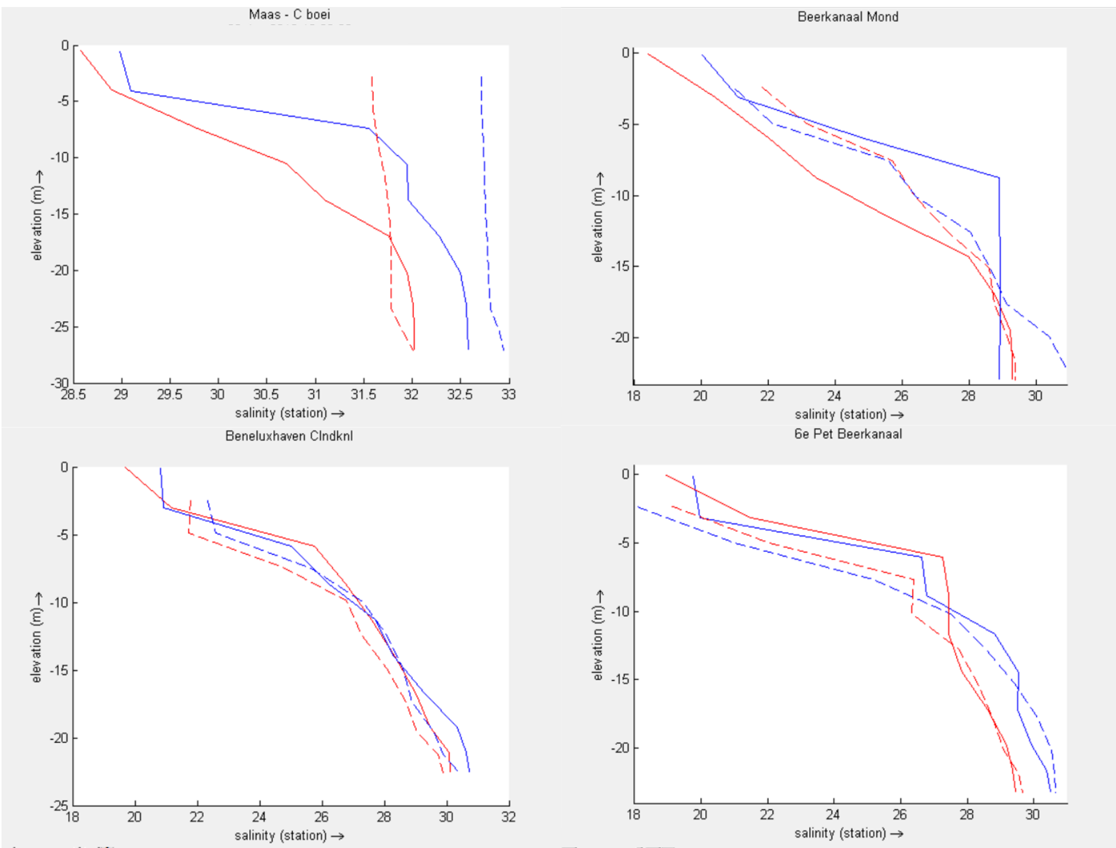
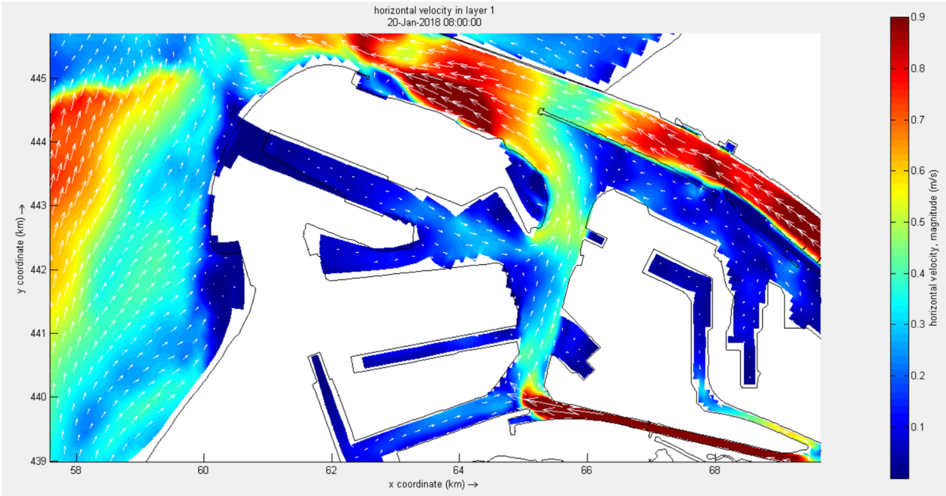
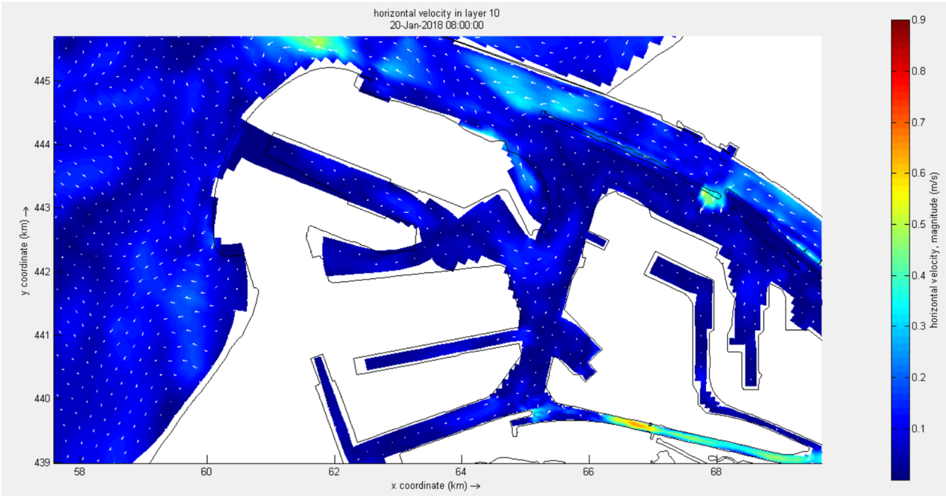
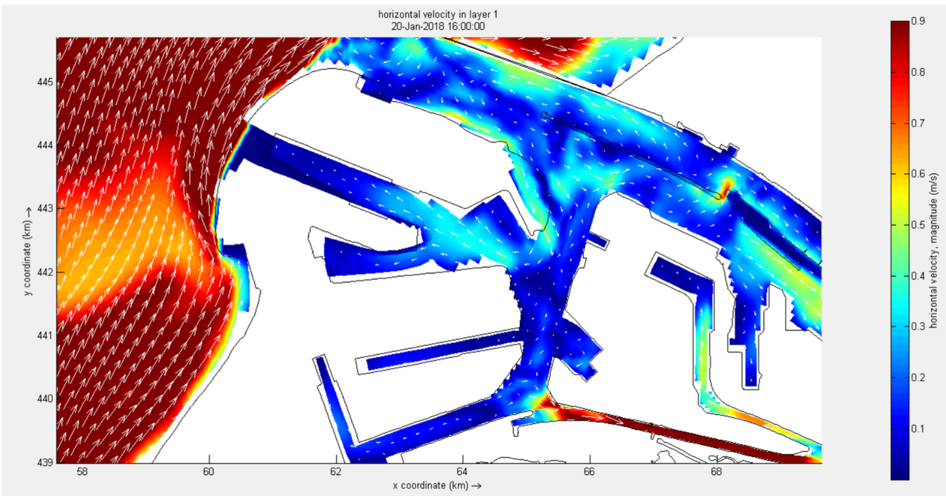


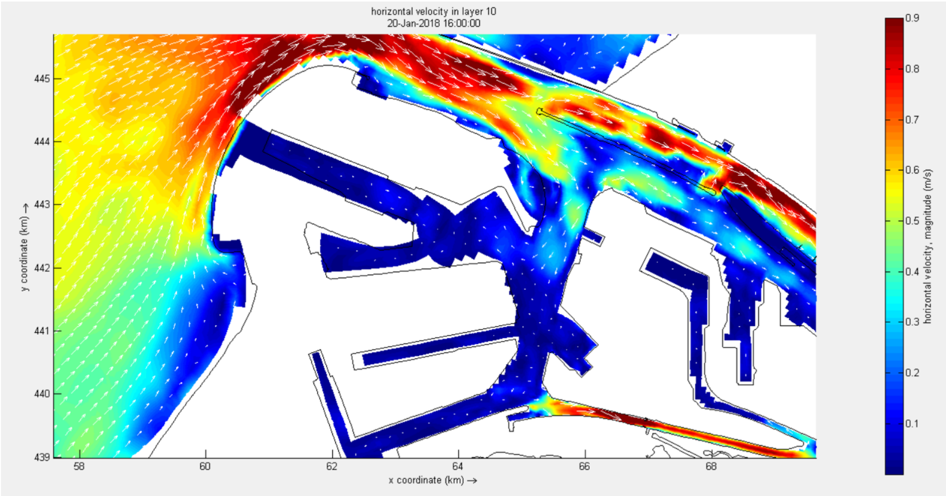
Figure F.5: Salinity profiles over depth at low-tide (dashed line) and high-tide (solid-line) of the measuring stations Maas-C boei, Beerkanaal Monding, Calandkanaal Europoort and 6e Petroleumhaven Beerkanaal of Simulation A (blue) and Simulation B (red)

F.3. Horizontal flow velocity





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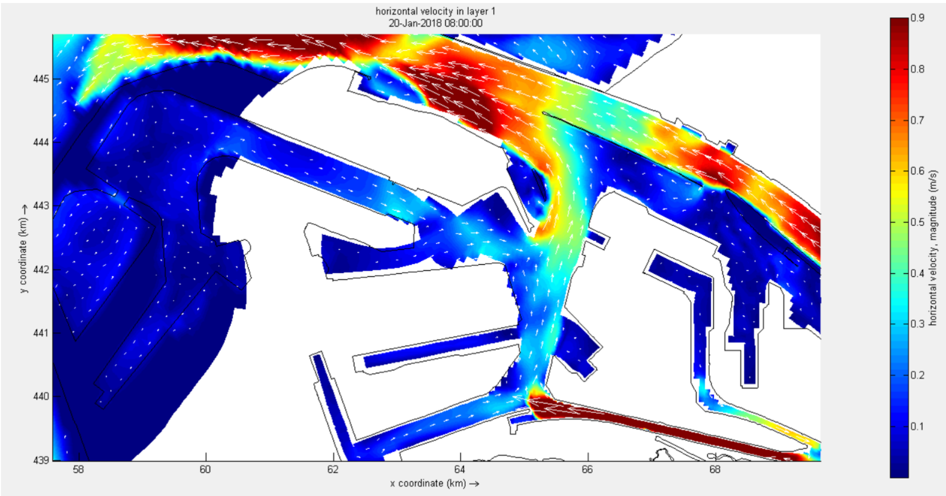
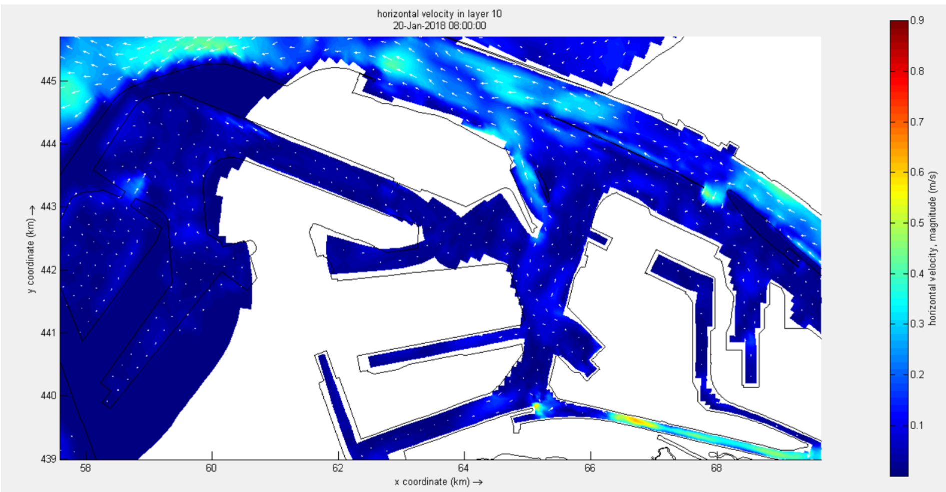
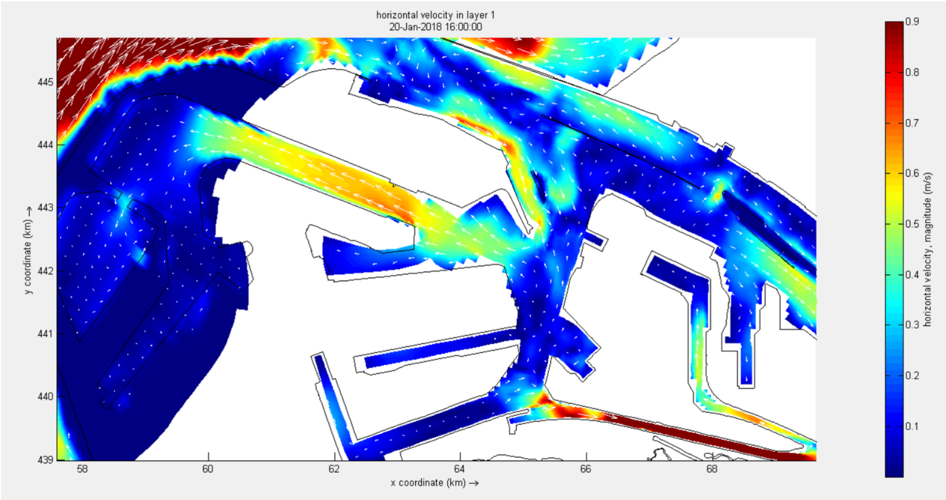
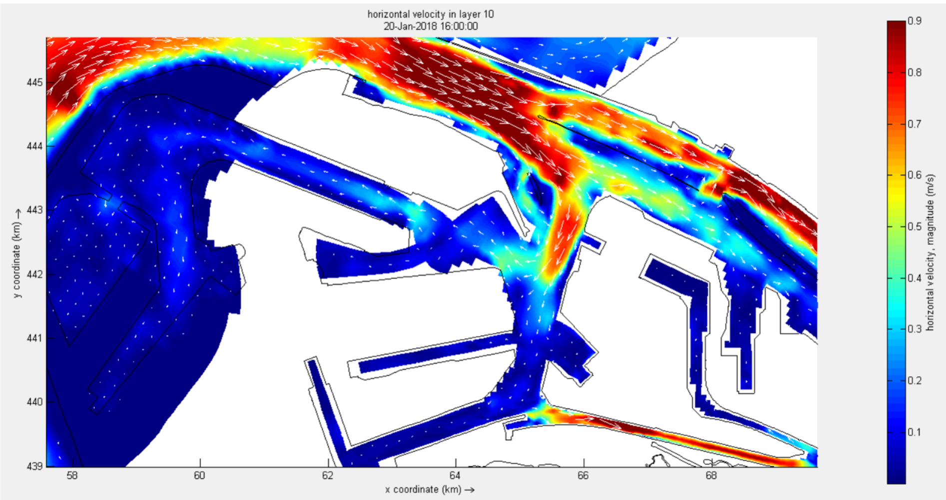
20-Jan-2018 16:00:00
y coordinate (km) →
x coordinate (km) →
horizontal velocity, magnitude (m/s)


horizontal velocity in layer 1
20-Jan-2018 08:00:00
y coordinate (km) →
x coordinate (km) →
horizontal velocity, magnitude (m/s)


horizontal velocity in layer 10
20-Jan-2018 08:00:00
y coordinate (km) →
x coordinate (km) →
horizontal velocity, magnitude (m/s)


horizontal velocity in layer 1
20-Jan-2018 16:00:00
y coordinate (km) →
x coordinate (km) →
horizontal velocity, magnitude (m/s)


horizontal velocity in layer 10
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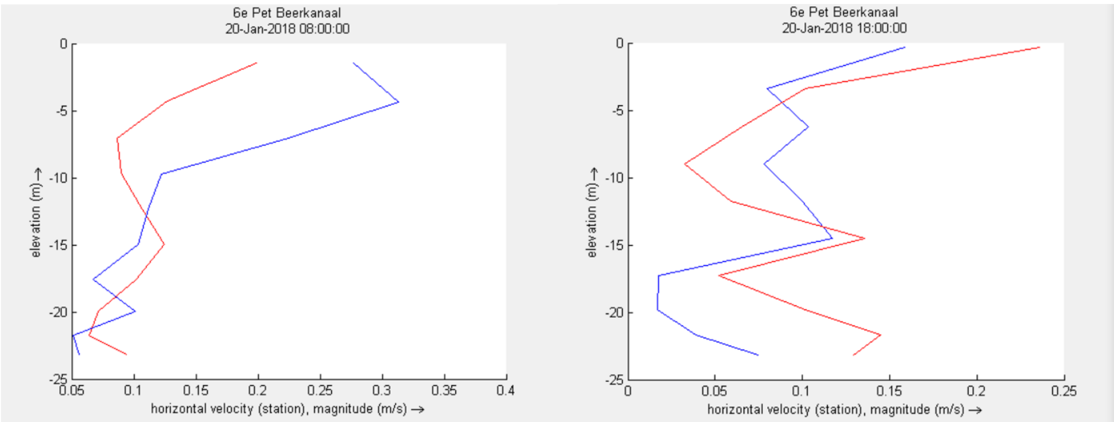
y coordinate (km) →
x coordinate (km) →
horizontal velocity, magnitude (m/s)


6e Pet Beerkanaal
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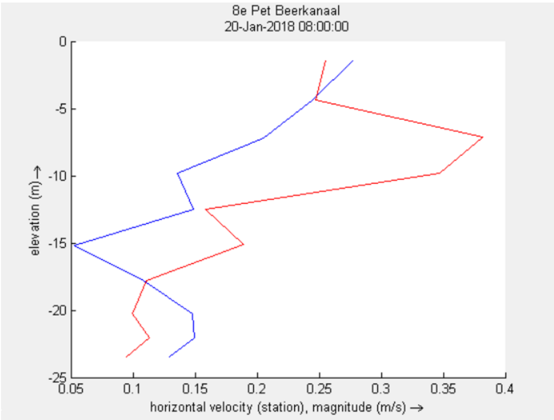
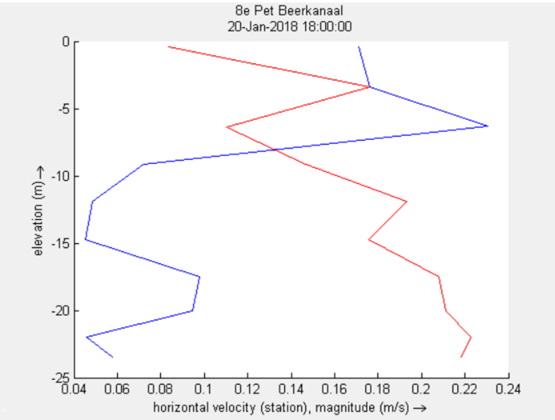
elevation (m) →
horizontal velocity (station), magnitude (m/s) →
6e Pet Beerkanaal
20-Jan-2018 18:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


8e Pet Beerkanaal
20-Jan-2018 08:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


8e Pet Beerkanaal
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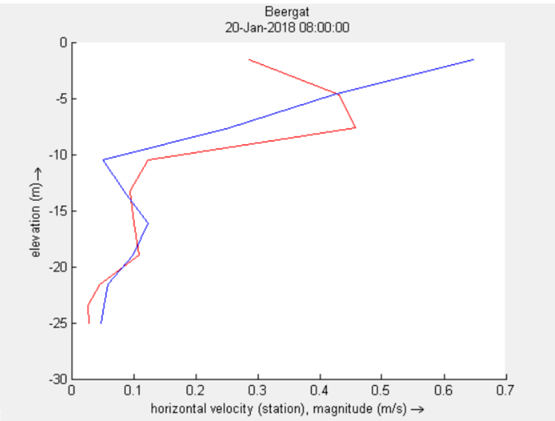
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


Beergat
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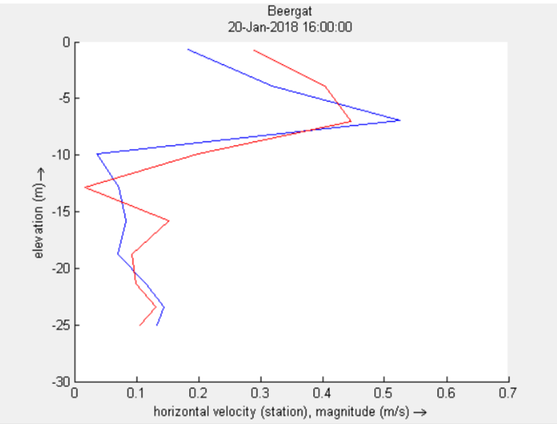
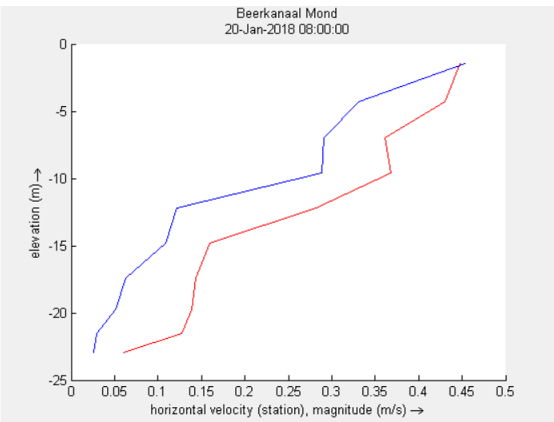
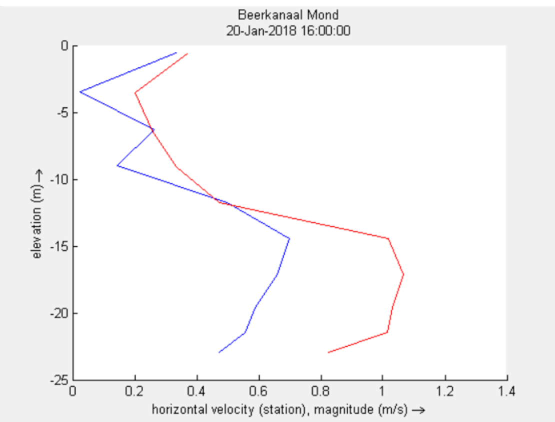
horizontal velocity (station), magnitude (m/s) →


Beergat
20-Jan-2018 16:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


Beerkanaal Mond
20-Jan-2018 08:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


Beerkanaal Mond
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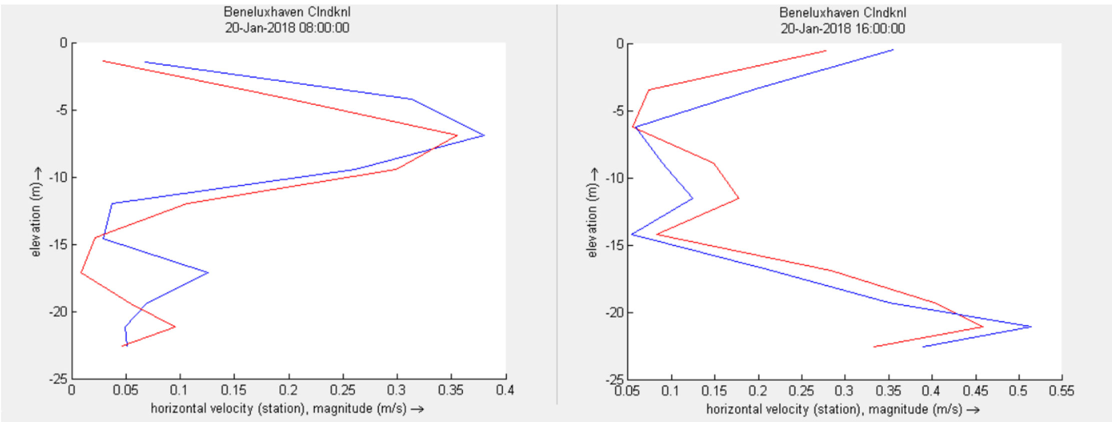
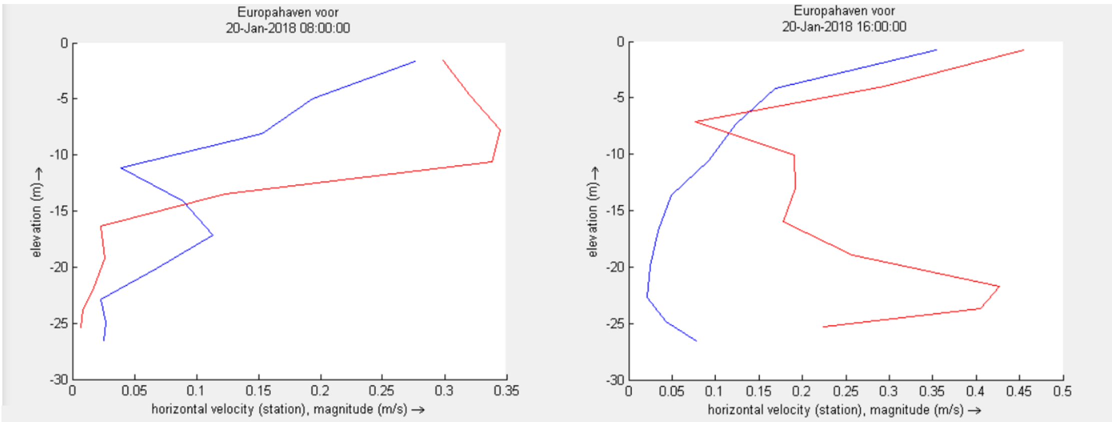
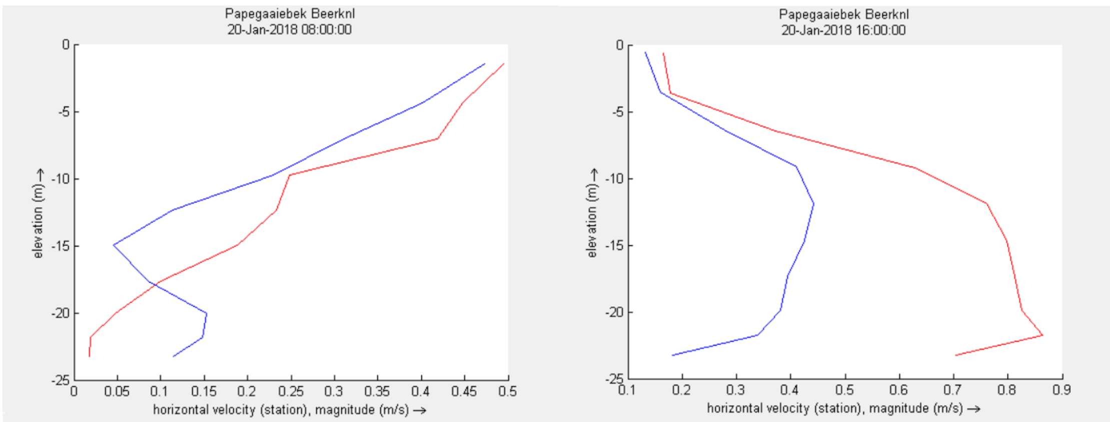
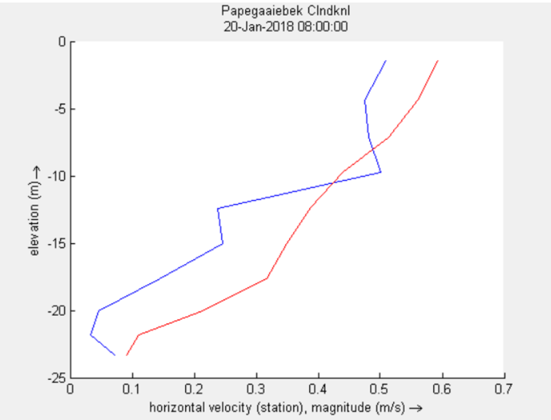
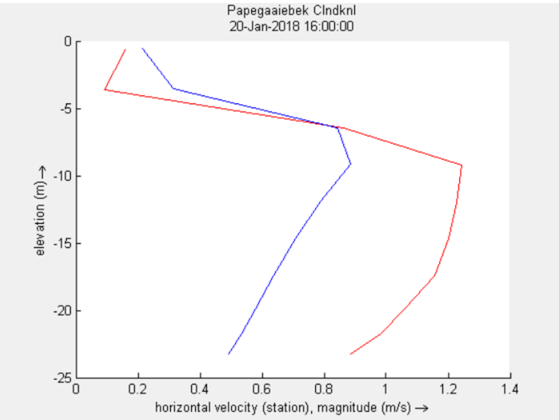
horizontal velocity (station), magnitude (m/s) →


Beneluxhaven Clndknl
20-Jan-2018 08:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →
Beneluxhaven Clndknl
20-Jan-2018 16:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


Europahaven voor
20-Jan-2018 08:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →
Europahaven voor
20-Jan-2018 16:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


Papegaaiebek Beerknl
20-Jan-2018 08:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →
Papegaaiebek Beerknl
20-Jan-2018 16:00:00
elevation (m) →
horizontal velocity (station), magnitude (m/s) →


Papegaaiebek Clndknl
20-Jan-2018 08:00:00
elevation (m) →
0
-5
-10
-15
-20
-25
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
horizontal velocity (station), magnitude (m/s) →


Papegaaiebek Clndknl
20-Jan-2018 16:00:00
elevation (m) →
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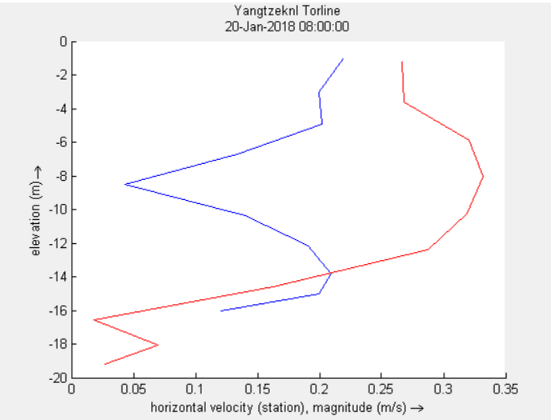
-5
-10
-15
-20
-25
0 0.2 0.4 0.6 0.8 1 1.2 1.4
horizontal velocity (station), magnitude (m/s) →


Yangtzeknl Torline
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elevation (m) →
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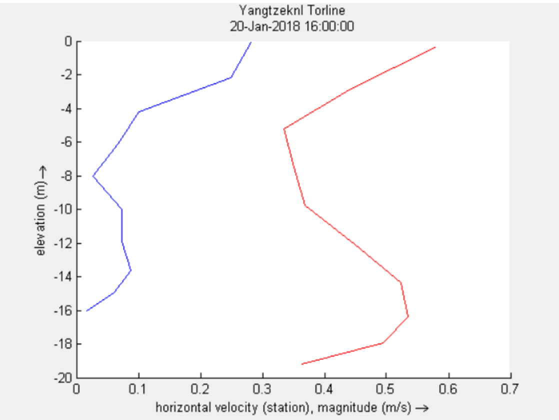
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
horizontal velocity (station), magnitude (m/s) →


Yangtzeknl Torline
20-Jan-2018 16:00:00
elevation (m) →
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
horizontal velocity (station), magnitude (m/s) →