Morphological development of the Haringvliet ebb tidal delta since 1970

A study based on the morphological development of individual morphological units

Winnie de Winter
31-Jan-14
Preface

This report is part of the internship I carried out at Rijkswaterstaat (Directorate-General of Public Works and Water Management) and Deltares to complete the Master of Science program Coastal Dynamics and River Systems at Utrecht University, The Netherlands. The Master of Science program is part of the study Earth, Surface and Water at Utrecht University, faculty of Geosciences.

The research study treated in this report is about the morphological development of the Haringvliet ebb tidal delta since the closure of the Haringvliet dam in 1970 until now. The morphological development is mainly described by the morphological development of the individual morphological units (shoals and channels). The investigated subject was very interesting, because the Haringvliet ebb tidal delta area has been exposed to a lot of large-scale human interventions and constructions. Such large-scale interventions have a large impact on the hydrodynamics and thereby the morphology of the former ebb tidal delta of the Haringvliet.

During this internship I was privileged to become acquainted with two very different organizations. At Rijkswaterstaat I learned a lot about the Dutch coastal policy, because I was invited to attend to several meetings about. Deltares had the necessities, such as the computer programs ArcGIS and Matlab, to execute the research. Both organizations provided supervisors who looked after the progress of my research resulting in a good cooperation between the two organizations. This is why I want to thank drs. Gemma Ramaekers (Rijkswaterstaat) and drs. Tommer Vermaas (Deltares) for their great support and supervision of my internship. I also want to thank drs. Quirijn Lodder (Rijkswaterstaat), drs. Rena Hoogland (Rijkwaterstaat) and Dr. Ad van der Spek (Deltares) for discussing the results of the research and giving advice. Lienes Hoek (Rijkswaterstaat) provided information about the dredging activities in the Slijkgat, so I want to thank him for his time and help. I also want to thank Prof. Gerben Ruessink for his supervision at Utrecht University and for providing me the contacts at Rijkswaterstaat.

January, 2014
Winnie de Winter
Abstract

In this report the morphological development of the Haringvliet ebb tidal delta since 1970 is established by the execution of a morphological research based on individual morphological units.

Due to the closure of the Haringvliet dam in 1970 the hydrodynamics in the Haringvliet ebb tidal delta changed from a tide dominated system into a system where waves are dominant in sediment transport processes. Because the ebb discharge decreased and therefore the hydrodynamics of the waves became more important, the ebb tidal delta increased in height and the edge of the delta retreated in landward direction. This causes troubles for the shipping lane of the Stellendam harbour in the southern part of the area, which fills in with sediment. This is the cause of the need for frequent monitoring and dredging of the channel.

The closure of the Haringvliet estuary was the main trigger to alter the hydro- and morphodynamics of the former Haringvliet ebb tidal delta. However, other large-scale human interferences, such as the construction of the Slufter and the Maasvlakte 2, might have contributed to alterations in the morphological features of the area.

To investigate the morphological development of the Haringvliet ebb tidal delta, sediment volume calculations were carried out using the data of the Vaklodingen. Additionally other morphological features, such as the surface area and the displacement of the centroid of a morphological unit, were investigated. The results are based on both the morphological features of individual morphological units (former tidal shoals and channels) and the entire ebb tidal delta.

It can be concluded that the development of the shoal at the seaward edge in the north of the area, the Hinderplaat, has been highly influenced by the construction of the Slufter and the sediment supply of the foreshore. The other shoals, the northern and southern Garnalenplaat, behave different and were eroding just after the closure of the Haringvliet until 1980. Thereafter the shoals increased in height, probably due to the construction of the Slufter, which may have influenced the course of the tidal flow. The altered course of the tidal currents probably created an increased deposition zone close to the dam. Finally, starting from 2001, all shoals will merge to form a large shoal in the central part of the former ebb tidal delta.

The water volume of most channels is decreasing after the closure of the Haringvliet dam, they fill in with sediment. An exception to this are the Bokkegat and Hindergat, these channels probably function as the in- and outlet of the tidal currents to the area and thus
remain open. The Slijkvat has been influenced by dredging activities, but just after the closure of the Haringvliet dam the water volume vastly decreased as well. The entire former ebb tidal delta is aiming for a new equilibrium state just after the closure of the Haringvliet dam. Between 1970 and 1980 the morphological changes are fast. After 1980 the rate of morphological change decreases and it seems that the area is going towards an equilibrium state. This new equilibrium is then temporarily disturbed by the construction of the Slufter and later the construction of the Maasvlakte 2 might have caused an increasing sediment volume of the area.

This research has been carried out in collaboration with Rijkswaterstaat and Deltares, which contributed to my graduation of the master Earth, Surface and Water / Coastal Dynamics and River Systems at Utrecht University.
Samenvatting (abstract in Dutch)

In dit verslag wordt de morfologische ontwikkeling van de buitendelta van het voormalige Haringvliet estuarium sinds de afsluiting van het Haringvliet in 1970 beschreven. Deze beschrijving wordt gedaan op basis van de individuele morfologische eenheden.

Door de afsluiting van de Haringvliet met de Haringvliet dam in 1970 zijn de hydrodynamische condities van de Haringvliet buitendelta veranderd van een getijgedomineerd systeem in een systeem dat gedomineerd wordt door de werking van golven. Door een verminderde ebstroom en een toename van de golfwerking vanuit zee, is de rand van de buitendelta in landwaartse richting verplaatst waardoor de voormalige buitendelta ophoogt. Dit veroorzaakt problemen voor een geul voor de scheepvaart naar de haven van Stellendam in het zuiden van het gebied. Deze geul vult zich op met sediment, waardoor er vaak baggerwerkzaamheden gedaan moeten worden.

De afsluiting van het Haringvliet estuarium was de hoofdoorzaak van de veranderingen in de hydro- en morfodynamica van de voormalige Haringvliet buitendelta. Echter, er zijn meerdere grootschalige menselijk ingrepen uitgevoerd in dit gebied, namelijk de bouw van de Slufter en de aanleg van de Maasvlakte 2. Deze ingrepen kunnen de morfologische ontwikkeling van het gebied ook beïnvloed hebben.

Om de morfologische ontwikkeling van de Haringvliet buitendelta te kunnen onderzoeken zijn er sediment volumes van de morfologische eenheden (de voormalige getij platen en geulen) en het gebied berekend, waarbij gebruik gemaakt is van de Vaklodingen in dit gebied. Naast de sediment volumes is er ook gekeken naar andere eigenschappen van de morfologische eenheden, zoals het oppervlak en de gemiddelde hoogte/diepte van de eenheid en de verplaatsing van het zwaartepunt.

Het water volume van bijna alle geulen neemt af na de afsluiting van het Haringvliet, omdat ze opvullen met sediment. Een uitzondering hierop zijn het Bokkegat en het Hindergat. Deze geulen functioneren hoogst waarschijnlijk als in- en uitgang van het getij tot het gebied van de buitendelta en blijven daardoor open. Het Slijkgat staat onder invloed van baggeractiviteiten, maar er kan wel gezegd worden dat net na de afsluiting van het Haringvliet het watervolume sterk is afgenomen.


Dit onderzoek was onderdeel van een samenwerking tussen Rijkswaterstaat en Deltares, wat heeft bijgedragen aan het behalen van de master Earth, Surface and Water / Coastal Dynamics and River Systems aan de Universiteit Utrecht.
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1. Introduction

This study focusses on the Haringvliet ebb tidal delta, which is part of the south-western Delta of the Dutch coast (figure 1.1). In this deltaic area three main rivers, the Scheldt, Rhine and Meuse, flow into the North Sea. Prior to the construction of the Delta Works the discharge of the rivers could freely flow into the North Sea. The river discharges combined with the tidal forces of the North Sea resulted in estuarine conditions for the inlets of the Dutch Delta Coast. However, after the big storm surge of February 1953, a large part of the south-western delta was flooded and many people died. To protect the inland area against the sea, it was decided that the landward site of the south-western delta needed to be closed off from the North Sea. This closure was part of the Delta Works, which consist of several dykes and dams along the North Sea coast. In the south-western Delta the Haringvliet and Grevelingen estuaries were entirely closed off from the sea. The dam built at the entrance of the Haringvliet basin consists of a closed part in the north and a sluices complex in the south, which can release fresh water of the Haringvliet to the North Sea during high river discharges (figure 1.2). In this research the area seaward of the Haringvliet dam is investigated.

Figure 1.1: The former Haringvliet ebb tidal delta (3) is part of the south western delta (2), The Netherlands (1). Source: Google Maps.
Due to the closure of the Haringvliet the estuarine system, dominated by the tide, was altered and wave processes became prevailing. Therefore the morphological processes of the Haringvliet ebb tidal delta changed dramatically and the area became a sink for sediment. This causes problems for the navigation channel, the Slijkgat, in the southern part of the area which gives access to the harbour of Stellendam. Because of the increased sedimentation, this channel needs to be dredged frequently. Alongside the dam construction, many other human interventions (table 1.1) influenced the morphology of this area as well. Because several human interventions occurred simultaneous or shortly after each other it is difficult to put the morphological changes down to one cause. However the construction of the dam appears to be the main factor in the system shift (Van der Spek, 1987; Tönis et al., 2002 and Cleveringa, 2008).

Table 1.1: Human interference in the Haringvliet delta area.

<table>
<thead>
<tr>
<th>Year</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>Damming of the Brielse Maas</td>
</tr>
<tr>
<td>1957 – 1970</td>
<td>Construction of the Haringvliet dam and sluices</td>
</tr>
<tr>
<td>1964 – 1976</td>
<td>Construction of the Maasvlakte 1</td>
</tr>
<tr>
<td>1970 – now</td>
<td>Dredging of the Slijkgat</td>
</tr>
<tr>
<td>1986 – 1987</td>
<td>Construction of the Slufter and excavation of the Hindergat</td>
</tr>
<tr>
<td>2008 – 2013</td>
<td>Construction of the Maasvlakte 2</td>
</tr>
</tbody>
</table>
The greater part of the research about the morphological change of the Haringvliet was carried out during the 80's and 90's of the past century until the beginning of the 21st century (e.g. Rijkswaterstaat, 1973; Auër, 1983; Van der Spek, 1987; Postma et al., 1990; Van Vessem, 1998; Tönis et al., 2002).

From literature it can be concluded that the ebb tidal delta of the Haringvliet is silting up. One of the recommendations made by Cleveringa (2008) was to improve the understanding of the sediment transport mechanisms in these kind of areas and the sources and sinks for sediment with their sediment transport rates. A morphological unit which receives sediment is determined as a sink for sediment and if it is losing sediment the morphological unit is a source for sediment. In this way it would be easier to predict future perspectives of closed deltaic areas. Preceding this research, morphological changes were observed at the scale of the entire Haringvliet delta. This has the disadvantage that it does not give a detailed view of individual morphological units. On the scale of individual morphological units a better distinction between sources and sinks for sediment in the delta can be made and a more detailed morphological development can be obtained.

Today the amount of bathymetric data has increased, which can be used for a more long-term analysis. Additionally, the analytical techniques have improved. In this research, the displacement of individual morphological units will be tested and other morphological features such as the sediment volume will be calculated in a more detailed way, based on individual morphological units.

Thus, the main goal of this research is to investigate the morphological development of the former Haringvliet ebb tidal delta on a scale of individual morphological units. The main research question is:

_How did the morphology of the Haringvliet ebb tidal area evolve since the delivery of the Haringvliet dam in 1970?_

This report continues as follows. In chapter 2 the research questions and the derived hypotheses are given. A literature review of the former research about the Haringvliet ebb tidal delta area is given in chapter 3. In chapter 4 the used methodology is described to obtain the results of this research, which are presented in chapter 5. The results will be followed by the discussion in chapter 6, leading to the conclusions (chapter 7). At the end of this report, in chapter 8, recommendations for further research are given which were brought up in the discussion of the results.
2. Research goals, questions and hypotheses

In this chapter the goal and questions of this research will be elaborated. First the goals are defined, using the remaining questions from literature, and the research questions are formulated in section 2.1. Thereafter, in section 2.2, hypotheses are given for the research questions.

2.1 Research goals and questions

As it was stated in the introduction, additional research is required to make a better understanding of the causes of the morphological changes in the former Haringvliet ebb tidal delta. Therefore, a more detailed research of the individual morphological units will be carried out.

The goals of this research are:

- Record the morphological changes which played a role in the morphological development of the Haringvliet ebb tidal delta after the closure of the estuary in 1970 with the use of sediment volume changes and the displacement of both the entire estuary and the individual morphological units.
- Investigate the breakpoint of the decrease in sedimentation rate near 1985 in both the individual morphological units and larger (sub-)areas.
- Investigate the tendency of the system to reach a morphological equilibrium.

The main research question will be:

How did the morphology of the Haringvliet ebb tidal area evolve since the delivery of the Haringvliet dam in 1970?

This question can be subdivided into several sub-questions:

1. a. How did the morphological units evolve since 1970, with respect to their surface area, sediment/water volume, shape, orientation and direction of migration?
   b. How did the entire ebb tidal delta evolve since 1970, with respect to its sediment volume, shape and orientation?
2. a. Do the morphological units act as a source (or sink) for sediment?
   b. What is the source and sink for sediment for the entire ebb tidal delta?
3. a. Do the morphological units show a change in sedimentation rate near 1985?
   b. Are there any specific areas where the change in sedimentation rate occurs?
4. Is the ebb tidal delta aiming for a new morphological equilibrium state?
5. Which hydrodynamic processes may have played a role in the sediment transport processes and change in morphology?

2.2 Hypotheses

In advance of the research, the research sub-questions are answered using hypotheses, which are listed below. The hypotheses are based on the literature about this subject. At the end of the research the hypotheses will be tested by comparison with the results.

Main question:

How did the morphology of the Haringvliet ebb tidal area develop since the delivery of the Haringvliet dam in 1970 until now?

The closure of the Haringvliet decreased the tidal prism. This caused an increase in the importance of waves in the sediment transport processes. As a result, the landward sediment transport increased. Current velocities in the tidal channels decreased due to relatively large cross-sectional areas and consequently channels filled in with sediment. Due to the smaller tidal prism, the system was shifting to a new equilibrium state. This shift signifies that morphological changes are fast just after a large interruption of the system and decreases exponentially in time. However, this system shift was probably hindered by the construction of the Slufter in 1985 (Tönis et al., 2002). After this construction it might be that the system shifted to a new equilibrium state again. However, in April 2013 the Maasvlakte 2 was delivered which is a large land reclamation west of the Maasvlakte 1 and the Slufter. The system might be influenced again such that the constructions interrupt the future equilibrium state. Eventually, the system will shift to a new equilibrium, adapted to the presence of Maasvlakte 2, if no new human interferences take place.

Main hypothesis: Human interferences influenced the hydrodynamics of the entire tidal system such that the equilibrium state of the area was disturbed and the system was heading for a new equilibrium state before the construction of Maasvlakte 2.

1. a. How did the morphological units evolve since 1970, with respect to their surface area, sediment/water volume, shape, orientation and direction of migration?

The geographical position of the morphological units mentioned below can be found in figure 3.3 (1965), 3.7 (1992) and 3.14 (2012).

The foreshore was eroding; its slope became less steep and migrated in landward direction.
Shoals such as the ‘Hinderplaat’ and the ‘Garnalenplaat’ are gaining sand and increase in height. Their shape becomes more elongated, perpendicular to the prevailing wave direction. The former tidal channels ‘Gat van Hawk’, ‘Bokkegat’, ‘Rak van Scheelhoek’ and ‘Slijkgat’ are filling with sediment such that the cross-sectional area of the channels is decreasing. In fact, the channel ‘Brielse Gat’ disappears. The ends of the channels turn into the alongshore direction. To maintain the accessibility of the Stellendam harbour, the Slijkgat, it is necessary to execute dredging activities.

In the north-western part of the delta called ‘Westplaat’ sediment is deposited, while the adjacent areas ‘Slufterdijk’ and ‘De Punt’ (the south-west directed edge of the coastline of Voorne) are eroding.

At the coast of Goeree horizontal sand waves are migrating towards the north and end up at the ‘Kwade Hoek’ where the beach extends towards the north-east.

Hypothesis 1.a.: The sediment volume of the shoals increases while the water volume of the tidal channels decreases and the foreshore is eroding. The orientation of the morphological features is turning in a perpendicular direction to the prevailing wave direction and the channels become more elongated. The morphological units migrate in landward direction.

1. b. How did the entire ebb tidal delta evolve since 1970, with respect to its sediment volume, shape and orientation?

Previous literature studies (Van der Spek, 1986; Tönis et al., 2002; Cleveringa, 2008) show that the entire ebb tidal delta is gaining sediment. Just after the construction of the Haringvliet dam the sediment volume increases very fast. After about 10 years, the sedimentation rate began to decrease. As it was shown by Tönis et al. (2002), the sedimentation curve of the northern part of the area differs from the sedimentation curve of the southern part. The sedimentation rate in the northern part was influenced by the construction of the Slufter. After the closure of the Haringvliet dam, sediment transport by waves became dominant over sediment transport induced by the ebb current. Therefore the point of where the ebb tidal current is extinguished by landward directed waves migrated in landward direction and thereby the edge of the ebb tidal delta did as well.

Hypothesis 1.b.: The sediment volume of the ebb tidal delta increased and the edge of the delta migrated in landward direction.
2. a. Do the morphological units act as a source (or sink) for sediment?
The foreshore and the ‘Hinderplaat’ are interconnected; the foreshore is a source for sediment and is eroded by waves. The waves transport the sediment in landward direction which is deposited on the ‘Hinderplaat’ (sink). The shoals and tidal channels are interconnected as well; the main event here is the sediment deposition in the tidal channels. Thus, the tidal channels are a sink for sediment. Sediment is deposited by the ebb currents. The sediment source for the ‘Slijkgat’ in the southern part of the area is the ‘Kwade Hoek’.

The ‘Westplaat’ receives sediment by alongshore currents from the south and the beach of Voorne, causing ‘De Punt’ to erode. Also sediment of the eroding part of the ‘Slufterdijk’ is deposited at the ‘Westplaat’.

The ‘Bollen van de Ooster’ are a source of sediment for the horizontal sand waves along the coast of Goeree. The sand will eventually be deposited at the ‘Kwade Hoek’, which in its turn fills the Slijkgat at its north eastern side.

Hypothesis 2.a.: The shoals and channels act as a sink for sediment, while the foreshore is a source for sediment.

2. b. What is the source (or sink) of sediment for the entire ebb tidal delta?
The sediment sources for the entire system are determined by the alongshore sediment transport. From the south, erosion of the Vlaamse Banken (sand bars in front of the Belgian North Sea coast), the North Sea itself and the discharges of the Thames, the Dover canal and the Western Scheldt provide sediment for the North Sea. Nowadays, after the construction of the Eastern Scheldt flood defence (finished in 1986), no significant sediment exchange between the Eastern Scheldt and the North Sea is present. This only occurred before the Eastern Scheldt flood defence was constructed. The sediment supply from the south is transported by alongshore currents to the north which is the prevailing direction for alongshore sediment transport. Due to the increased dominance of waves, the sediment supply from the south west increased, because this is the prevailing wave direction.

Hypothesis 2.b.: The entire ebb tidal delta receives sediment from the south by alongshore sediment transport and from the south west by wave induced sediment transport. Sediment leaves the system at the north side by alongshore currents.
3. **a.** Do the morphological units show a sudden change in sedimentation rate near 1985? 

In previous research it was noticed that there is a sudden change in sedimentation rate near 1985 (Tönis et al., 2002; Zijlstra, 2013). Therefore it is expected that the same phenomenon would be visible in the individual morphological units as well. However, Tönis et al. (2002) showed that the sedimentation rate is dependent on the location in the Haringvliet delta area and thus individual morphological units might show different sedimentation rates dependent on their location in the ebb tidal delta.

Hypothesis 3.a.: The occurrence of a change in sedimentation rate near 1985 is dependent on the location of the morphological unit in the ebb tidal delta. The units in the northern part show a change in sedimentation rate, while the units in the south do not.

3. **b.** Are there any specific areas where a sudden change in sedimentation rate near 1985 occurs? 

As it was stated in 1.b. and 3.a., the sedimentation rate through time is dependent on the location in the ebb tidal delta. The northern part of the delta is influenced by the construction of the Slufter whereas the southern part seems to be aiming for an equilibrium state.

Hypothesis 3.b.: The northern part of the area shows a change in sedimentation rate near 1985, while the southern part does not.

4. Is the ebb tidal delta aiming for a new morphological equilibrium state? 

Before the delivery of the Maasvlakte 2, the system was adapting to the reduced tidal prism. Since the pattern of the tidal currents has changed, the ebb tidal delta lost its function and the area is heading towards a more or less straightened shape with the rest of the coastline. Because the rate of morphological change is exponential in time, the rate of morphological adaptation decreases in time. Large adaptations occurred just after the construction of the dam and diluted after about 10 years (Van der Spek, 1987). Thereafter the degree of morphological changes decreased, which can be considered that the system was heading to a new equilibrium state.

Hypothesis 4: The ebb tidal delta reached a new morphological equilibrium since the construction of the dam in 1970 until the construction of the Maasvlakte 2.
5. Which hydrodynamic processes may have played a role in the sediment transport processes and change in morphology?

Due to the closure of the Haringvliet, the tidal prism of the area seaward of the dam decreased. Therefore all morphological elements in this area were too large in relation to the hydrodynamic regime. Because the ebb tidal current velocities decreased, sediment transport due to waves became relatively more important. Current velocities in the tidal channels decreased which resulted in sedimentation and the tidal channels were filling with sediment.

Hypothesis 5: Sediment transport by waves is dominant over the tidal sediment transport.
3. Literature summary

In this chapter the subject of interest will be introduced. Information found in literature about the morphology of the Haringvliet delta before and after the closure of the dam will be elaborated. The hydrodynamics and morphology of the Haringvliet ebb tidal delta before the dam closure will be elaborated in section 3.1. In section 3.2 the changes in hydrodynamics and morphology after the closure of the Haringvliet will be discussed and future perspectives influenced by the construction of Maasvlakte 2 will be given.

3.1 Hydrodynamics and morphology of the ebb tidal delta before the closure of the dam (until 1970)

The morphological situation of the Haringvliet ebb tidal delta before the closure of the dam is shown in figure 3.1. The morphological features are marked by the numbers I-VII. The ebb delta contained tidal shoals and channels as a result of a hydrodynamic regime dominated by the tidal forces. The main channel (“Rak van Scheelhoek”, IV), which connects the Haringvliet basin and the North Sea, ends up in a bifurcation of the “Gat van de Hawk” channel (II) and the “Bokkegat” channel (III) at the seaward side. Another tidal channel is situated in the southern part of the delta called the “Slijkgat” (VI). Two main shoals can be distinguished, the “Zeehondenplaat” (I) in the north and the “Garnalenplaat” (V) in front of the inlet to the Haringvliet basin. Connected to the northern coast of Goeree, the “Kwade Hoek” (VII) is situated.
Figure 3.1: Bathymetry of the Haringvliet estuary in 1965. The bathymetry is based on vaklodingen data of the Directorate-General of Public Works and Water Management (in Dutch: Rijkswaterstaat). Source: Kustviewer, Rijkswaterstaat; Deltares; Nelen & Schuurmans http://test.kustviewer.lizard.net/kml/.

**Tide**

Before the closure of the Haringvliet the estuary was long and straight shaped. The length of the estuary caused a phase difference between the tidal current velocities inside the estuary and the velocities of the alongshore tidal current (figure 3.2) (Sha and Van den Berg, 1993). Inside the estuary maximum current velocities, both during flood and ebb, were reached earlier than outside the estuary. Along the Delta Coast, the tide comes in from the south and travels to the north and it is leaving in the reversed direction. Inside the estuary the flow direction in the channels during flood was landward (figure 3.3, left picture). During ebb the direction of these currents was pointed towards the sea (figure 3.3, right picture). Wave induced currents entering the area from the North Sea increased the flood currents and retarded the ebb currents. The channels of the estuary were flood dominant (Tönis et al., 2002), so the maximum flow velocities were in flood direction.
Figure 3.2: Current velocities inside and outside the estuary before the dam closure. The positive values are representing the ebb current. Source: Tönis et al., 2002.

Figure 3.3: Tidal currents in advance of the Haringvliet dam closure. The current directions in the left picture are during high water near Hoek van Holland and the right picture shows the situation during 6 hours before high water. Note: the length of the arrows does not indicate the magnitude of the currents. Source: Van der Spek, 1987.

*Morphology*

Before the human interference and coastal engineering constructions, the Haringvliet was acting as an estuary under natural conditions. In figure 3.4 a schematic representation of this situation is shown. The ebb and flood currents were continuing inside the Haringvliet basin. During flood water was entering the Haringvliet basin through these flood channels. During ebb, water flowed in seaward direction and decelerated due to the increase in cross-sectional width towards the sea. The decrease of flow resulted in deposition of sediment and
the formation of the ebb tidal delta (Van der Spek, 1987). The sediment volume stored in the ebb tidal delta is determined by both the tidal prism and the wave energy (Walton and Adams, 1976). Thus, not only the ebb currents (determined by the tidal prism) transport sediment in seaward direction, waves transport sediment in landward direction as well.

Ever since 1950 the morphology of the estuary has been influenced by human interference and coastal engineering structures (Tönis et al., 2002) (table 1.1). But compared to the construction of the Haringvliet dam, the period between 1950 and 1965 is a period of relatively little human influences on the ebb tidal delta of the Haringvliet. In this time span the coast is expanding in seaward direction and the surface area of the intertidal area increases (Van der Spek et al., 1987). The seaward extension was caused by a larger sediment transport out of the tidal basins compared to the wave driven sediment transport in landward direction (Postma et al., 1990). Thus before the closure of the Haringvliet, the ebb currents were dominant for sediment transport relative to the waves and thus the ebb currents were retarded at a more seaward location.

![Schematic picture of the hydrodynamics and morphology before the closure of the dam](image)

**Figure 3.4:** Schematic picture of the hydrodynamics and morphology before the closure of the dam. Source: Cleveringa, 2008.

### 3.2 Hydrodynamics and morphology of the ebb tidal delta after the closure of the Haringvliet dam

The morphology of the Haringvliet ebb tidal delta in 1992, 22 years after the closure of the dam, is shown in the bathymetric map of figure 3.5. The morphological features are indicated by the numbers I – X. In the northern part of the delta the land reclamation of the Maasvlakte 1 (constructed in the period 1964 – 1976) with the Slufter and Slufterdijk (constructed in the
Morphological development of the Haringvliet ebb tidal delta since 1970

January, 2014

Rijkswaterstaat, Deltares and Universiteit Utrecht

period 1986 – 1987) (I) is now present. Eastward from there a shallow area called “Westplaat” (II) has developed. The tidal channels “Gat van de Hawk” and “Bokkegat” disappeared and the “Rak van Scheelhoek” (VI) filled in with sediment and consequently became shallower. One small channel in the north called the “Hindergat” (III) and one in the south called “Slijkgat” (VII) still exist. The shoal at the seaward end of the delta became shallower and is now called the “Hinderplaat” (IV). Furthermore, the “Garnalenplaat” and the “Kwade Hoek” (V and VIII, respectively) are still present. At the west coast of Goeree the horizontal sand waves (IX) (Maranus and Verhagen, 1987) migrate along the coast towards the north. The “Bollen van de Ooster” (X) act as a sediment source for these sand waves.

Figure 3.5: Bathymetry of the Haringvliet estuary in 1992. The bathymetry is based on vaklodingen data of the Directorate-General of Public Works and Water Management (in Dutch: Rijkswaterstaat). Source: Kustviewer, Rijkswaterstaat; Deltares; Nelen & Schuurmans http://test.kustviewer.lizard.net/kml/.

**Tide**

Due to the closure of the Haringvliet dam, the shape and surface area of the estuary have changed dramatically. This resulted in a change of the tidal dynamics. The reduction of the estuarine area resulted in a shift of the phase of the tidal velocities in the estuary (Sha and Van den Berg, 1993). Now the current velocities are almost in phase, such that the maximum current velocities in- and outside the estuary occur at almost the same time (figure 3.6) (Tönis et al., 2002). Additionally, in figure 3.6 it can also be seen that the pattern of the
current velocities follows the pattern of the water levels: the ebb current reaches its maximum when the water level is at its lowest point. Compared to the situation before the closure, the tide shows a more circular pattern through the ebb tidal delta and has the same direction as the tide at sea instead of an in- and outflow of the tide in the tidal basin (figure 3.7) (Van der Spek, 1987). The channels in the south-western part of the area let the flood currents come in, which will leave the area through the north-western channels. During ebb, the currents are flowing in opposite direction. Just like the situation before the closure of the Haringvliet, the channels in the back of the estuary are still flood dominant as it was shown by model calculations (Tönis et al., 2002).

During high river discharges, the sluices of the dam are able to release the fresh water outflow of the Haringvliet basin during ebb. On average, the sluices of the dam are able to release a volume of about $22\times10^6$ m$^3$ fresh water every tidal cycle (Van Vessem, 1998). This additional “ebb current” discharges through the Slijkvet by which the Rak van Scheelhoek loses its function as an ebb discharge channel (Van der Spek, 1987).

Figure 3.6: Current velocities in- and outside the estuary after the dam closure. The positive values represent the ebb current. Source: Tönis et al., 2002.
Waves

The closure of the Haringvliet has caused an increase in wave dominance with respect to the dominance of the tide (Cleveringa, 2008). This change in hydrodynamics reflects on the morphodynamics of the ebb tidal delta in a sense that the system is completely different compared to the situation in the past (Kohsiek and Mulder, 1988; 1989). The importance of incident waves from the north-west decreased due to the land reclamation in the northern part of the estuary (Maasvlakte 1 and Slufter) (Tönis et al., 2002). In April 2013 the construction of Maasvlakte 2 was finished, which is an extension at the west side of the land reclamations Maasvlakte 1 and the Slufter. Until now the effect of the Maasvlakte 2 on the wave climate is not exactly known. No literature about the effects is available probably due to the fact that the effects are not sufficiently present in such a short time period. However, like the Maasvlakte 1 and the Slufter it is again a seaward extension of land so it might have an additional effect on the former Haringvliet ebb delta such that it decreases the impact of the north-western incident waves.

Additional, because accretion in the estuary increased since the closure of the Haringvliet, the area became shallower causing an increase in the dissipation of wave energy. This results in a decrease of wave impact near the dam (Rijkswaterstaat, 1973).
**Morphology**

The morphology of the delta changed dramatically after the closure of the Haringvliet. A schematic representation is shown in figure 3.8. The most prominent changes occurred within the first 10 years after the closure. In the period 1980-1982, the rate of morphology changing decreases (Van der Spek, 1987). Others (e.g. Tönis et al., 2002; Zijlstra, 2013) state that there is another change in the sedimentation rate of the ebb tidal delta after 1985. From 1971 to 1982, $21 \times 10^6$ m$^3$ of sand is deposited landward of the 5 m depth line relative to NAP (Dutch Ordnance Level) (Auër, 1983), which is about $2 \times 10^5$ m$^3$ per year. The entire ebb tidal delta of the Haringvliet is now a sink for sediment. Whether a closed ebb tidal delta becomes a sink or a source for sediment is for a large part dependent on the position of the closure relative to the coastline (Wang et al., in press). In the case of the Haringvliet delta, the dam is located landward compared to the dam of for instance the Grevelingen basin. So the area with infilling channels is relatively large compared to the eroding foreshore area and thus the area is gaining sediment. Additionally, most of the eroded sediment of the foreshore is deposited on the ebb tidal bar. As it has been noted earlier, after the dam construction wave driven transport processes became dominant over the tidal sediment transport. Due to the increasing dominance in sediment transport by waves the foreshore was eroding and migrated in landward direction (Postma et al., 1990) (figure 3.9). As a result, the slope of the foreshore became gentler and the orientation of the foreshore changed in a direction which is more perpendicular to the prevailing wave direction. A shoal has been developed at the edge of the foreshore, called Hinderplaat (Postma et al., 1990). This shoal was mainly developed due to onshore sediment transport by waves, where the eroding foreshore functioned as a sediment source. Just like the foreshore the shoals are directed perpendicular to the prevailing wave direction and they were migrating in landward direction. The shoals at the landward side (Garnalenplaat (V in figure 3.5)) are lowered because the sediment supply to these shoals reduced, causing an increased dominance of eroding waves. The landward shoals migrated in the direction of the prevailing wave direction (Postma et al., 1990). The seaward ends of the tidal channels became shallower due to sand sedimentation and turned into a more parallel direction with the tide at the North Sea (Postma et al., 1990). Additionally, the channels close to the dam and the ebb channels silted up with mud.
Morphological development of the Haringvliet ebb tidal delta since 1970

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Figure 3.8: Schematic picture of the hydrodynamics and morphology after the closure of the Haringvliet dam. Source: Cleveringa, 2008.

Figure 3.9: Development of the edge of the Haringvliet ebb delta in the period 1964 – 2004. The slope of the foreshore became gentler and migrated in landward direction. The right side of the figure is the seaward side of the ebb tidal delta. Source: Cleveringa, 2008.

Dredging

The Slijkgat, which is a former tidal channel used as a shipping lane to the harbour of Stellendam, is also filling with sediment. When the sluices are opened they flush part of the sediment out of the Slijkgat, but this is not sufficient enough whereby the Slijkgat still needs to be dredged to maintain its shipping lane (Tönis, 2000). There are three problematical areas, where frequent dredging is needed to maintain the sufficient water depth of
approximately NAP -5 m for shipping (L. Hoek, Rijkswaterstaat, personal oral communication, 6 November 2013) (figure 3.10). The Slijkgat is monitored with a frequency of 4 times a year. When the water depth does not meet the sufficient depth of approximately NAP -5 m, the channel will be dredged. The annual dredged volumes from 2005 until 2012 are listed in table 3.1. The annual dredged volumes of 2011 and 2012 show a large increase. One of the reasons might be that the construction of the Maasvlakte 2 increased the suspended matter in the water column resulting in an increase in sediment deposition in the Slijkgat (L. Hoek, Rijkswaterstaat, personal oral communication, 6 November 2013). However, this has not been proved yet. The most seaward problematic location (“Drempel bij Hindergat” figure 3.10) is rapidly filling with sediment due to the migration of the southern part of the Garnalenplaat in south-west direction. Second, at the northward side of the Kwade Hoek (“Drempel bij Kwade Hoek” in figure 3.10), two channels meet which results in a shallow area at the location where the channels meet. And third, another cause of the sediment fill-in of the Slijkgat is the Kwade Hoek itself, which is a north-eastern migrating extension of the coast of Goeree formed by “horizontal sand waves” (in Dutch: horizontale zandgolven) along the coast of Goeree. These horizontal sand waves are features along the coast of periodic alternating erosion and sedimentation (Maranus and Verhagen, 1987). Most likely, the ‘Bollen van de Ooster’ periodically supply sand to generate the horizontal sand waves.

Figure 3.10.: Problematic areas of the Slijkgat where intensive dredging is needed to maintain the shipping lane to the harbour of Stellendam. The Dutch words “drempel bij” means “interference at”. Source: L. Hoek, Rijkswaterstaat, personal communication, 6 November 2013.
Table 3.1: Annual dredging volumes from 2005 until 2012. Source: (L. Hoek, Rijkswaterstaat, personal communication, 6 November 2013).

<table>
<thead>
<tr>
<th>Year</th>
<th>Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>150,000</td>
</tr>
<tr>
<td>2006</td>
<td>84,000</td>
</tr>
<tr>
<td>2007</td>
<td>103,000</td>
</tr>
<tr>
<td>2008</td>
<td>400,000</td>
</tr>
<tr>
<td>2009</td>
<td>200,000</td>
</tr>
<tr>
<td>2010</td>
<td>250,000</td>
</tr>
<tr>
<td>2011</td>
<td>761,000</td>
</tr>
<tr>
<td>2012</td>
<td>736,491</td>
</tr>
</tbody>
</table>

Construction of the Slufter

The construction of the Slufter (1986 – 1987) in the northern part of the delta caused another interruption of the system (Tönis et al., 2002) (figure 3.11). When the entire ebb tidal delta is divided in a northern and southern part it can be observed that the southern part is going towards an equilibrium sediment volume (figure 3.11, centre), which will be probably reached by 99% in the year 2020 (Tönis et al., 2002). However, the northern part contains a vast amount of sediment volume relative to 1970 since 1990 (figure 3.11, right). It is assumed that such a large increase in sediment volume can only be induced by human interventions and thus the construction of the Slufter (Tönis et al., 2002). Sediment volume changes that occur naturally usually show gradual changes instead of sudden large changes. A large dam was built around the Slufter and therefore a lot of sediment was added to the area causing a sudden increase in sediment volume. The change in the rate of increase in sediment volume was also observed by Zijlstra, 2013, especially around the coast of Voorne.

Figure 3.11: Sediment volume of the Haringvliet delta through time of the entire delta (left), the southern part of the delta without the Slufter (centre) and the Slufter (right).
Present morphology
The present morphology of the Haringvliet ebb tidal delta is shown in figure 3.12. In April 2013 the new land reclamation Maasvlakte 2 (constructed in the period 2008 – 2013) (I) has been delivered. It is connected to the Maasvlakte 1 and Slufterdijk (II) at the westward side. The Westplaat (III), Hindergat (IV), Slijkgat (VI), Kwade Hoek (VII), the horizontal sand waves (VIII) and Bollen van de Ooster (IX) are still present. However, the inner area of the Haringvliet delta differs compared to the previous situations. The Hinderplaat (V) is now centred in the ebb tidal delta.

At present, the main transformation of the area is the construction of the Maasvlakte 2. As it has been noted earlier, the effect on the morphology of the Haringvliet delta area is not known nowadays, but it might act as a shelter for the area against incoming waves from the north-west.

Figure 3.12: Bathymetry of the Haringvliet estuary in 2012 modified with the 2013 situation when the Maasvlakte 2 has been delivered. The bathymetry is based on vaklodingen data of the Directorate-General of Public Works and Water Management (in Dutch: Rijkswaterstaat). Source: Kustviewer, Rijkswaterstaat; Deltares; Nelen & Schuurmans http://test.kustviewer.lizard.net/kml/.
4. Methodology

In this chapter the methodology of the research will be elaborated. First, in section 4.1, it will be described what kind of data is used in this research. Thereafter, it will be described how the data has been analysed. I used Matlab, ArcMap and the OpenEarthTools of Deltares to analyse the available data.

4.1 Data


4.2 Analysis

4.2.1 Definition of morphological units

The morphological units are defined in the vaklodingen relative to a certain reference depth, which is determined by contour lines of the bathymetric data. Morphological features are defined relative to or at this reference depth. The depth of a contour line needs to be suitable such that it can function as a reference surface for all morphological units of a specific class (shoals or channels) during the recorded period. It also has to be taken into account that the contour lines around a specific area is a closed polygon which covers the morphological unit at its largest possible extension. For the shoals the depth of NAP -2.2 m was suitable, such that the depth contour lines of the shoals do not connect to the coastline in most of the time series. The channels are defined in a similar way like the shoals, but with the reference depth of NAP -5 m. The Slikkgat is an exception to this and is defined at the reference depth of NAP -4.4 m; otherwise the channel was split up into several parts and was not recognizable as a channel. The other channels are still defined at a reference depth of NAP -5 m because shallower reference depths resulted in problems where the contour lines of the channels were connected to the contour lines of the foreshore. For this latter reason the
other channels were not defined at this reference depth, and the polygons would connect to the depth contour lines of the foreshore. Sometimes the contour lines were modified in cases where the depth polygon connects to the coastline or when the polygon is situated near the boundary of the data and thus a “no data area”. An example is given in figure 4.1. The black lines are the original depth contour lines based on the bathymetric data, where the red dashed line is the entire polygon line including the final large shoal formed since 2001. To select solely the large shoal, the polygon is clipped at the northern narrow part (blue line). The clip locations are partly an arbitrary decision, however the situations before and after are taken into account.

Figure 4.1: Modification of the contour line of the Supershoal.
4.2.2 Definition of the morphological features

Surface area
The surface area of the morphological units is based on the polygons which define the individual units in the vaklodingen and is calculated by:

\[ A = N \times \text{grid area} \quad [1] \]

where \( A \) is the surface area in \( \text{m}^2 \), \( N \) is the number of grids inside the polygon with a value \( \geq \) the reference depth and the grid area of the vaklodingen is \( 400 \text{ m}^2 \) (20x20 m).

Sediment volumes / water volume
The sediment volumes (or water volumes) are calculated based on the bed level height of the bathymetric data (vaklodingen). Sediment volumes are used to determine the volume of a shoal and water volumes are used for the channels. The total volume of a certain morphological unit is calculated by:

\[ V = \sum (h \times \text{grid area}) \quad [2] \]

where \( V \) is the sediment (or water) volume in \( \text{m}^3 \), \( h \) is the absolute \( z \)-value (m) of the bathymetric data \( \geq \) the reference depth and the grid area of the vaklodingen is \( 400 \text{ m}^2 \) (20x20 m). Sedimentation and erosion are defined in a different way for the shoals and channels, because the definition of volume differs for the shoals and channels. An increase in shoal volume means that the sediment volume of the school increases and thus sedimentation takes place. A decrease in shoal volume therefore indicates erosion. For the channel volume these definitions are the other way around. A decrease in channel volume means that the water volume inside the channel is decreasing which indicates the infill of the channel (sedimentation). An increase in channel volume means that the channel deepens or becomes broader and thus erosion takes place.

Average height / average depth
The average height of the shoals and average depth of the channels are defined by the division of the sediment volume (or water volume) by the surface area of the morphological units.
Direction of migration
Once the polygons around the morphological units were defined in the bathymetric data of the Vaklodingen, the centre of gravity (centroid) of the surface area was calculated. The centroid is a spatial averaged point of the polygon which defines a certain morphological unit. The x- and y-coordinates of the centroid are calculated by the following equations:

\[ x_{\text{centroid}} = \frac{\sum (x_{i+1}+x_i) \times a \times y_i}{A} \]  \hspace{1cm} [3]

\[ y_{\text{centroid}} = \frac{\sum (y_{i+1}+y_i) \times x_i \times a}{A} \]  \hspace{1cm} [4]

\[ a = \frac{x_{i} \times y_{i+1}}{x_{i+1} \times y_{i}} \]  \hspace{1cm} [5]

where \( x_{\text{centroid}} \) is the x-coordinate of the centroid (m), \( y_{\text{centroid}} \) is the y-coordinate of the centroid, \( x \) are the x-coordinates of the polygon, \( y \) are the y-coordinates of the polygon and \( A \) is the surface area of the polygon. The subscript \( i \) represents the location of the x- and y- values along the polygon line.

\[ 4.2.3 \text{ Sediment volume calculations of the entire area} \]

The area for the calculation of the sediment volume of the entire ebb tidal delta is shown in figure 4.2. The boundaries of this area are basically determined by the NAP -10 m and NAP -1 m depth contour lines of the bathymetry in 1970. The seaward boundary is based on the NAP -10 m depth contour line of the foreshore, because this is the edge between the landward part where considerable changes do occur and the seaward part where almost no erosion or sedimentation takes place. This is based on the erosion/sedimentation map of the period 1970 – 2012 (figure 4.2). Figure 3.9 also shows that there is almost no morphological activity below NAP -10 m. Close to the coastline the NAP -1 m depth contour line is used as the landward boundary of the calculation area. At the southwest edge of the area there is a notch in the boundary. This is chosen based on the extent of the data, because a lot of time steps contained ‘no data’ in this area. The other part of the defined area is covered for at least 1% in all used time steps. The north part of the area, where the Slufter was built between 1986 and 1987, is not included in the calculation area because no data is available from 1989 in this area. The total area is approximately 88 km\(^2\). The remaining time steps with sufficient data are: 1970, 1972, 1976, 1979, 1980, 1984, 1986, 1992, 1998, 2003, 2006, 2009, and 2012.

The sediment volume of the entire delta was calculated with the use of equation 2, where \( V \) is the sediment volume in m\(^3\), \( h \) is the absolute z-value (m) of the bathymetric data \( \geq \) the reference depth and the grid area of the vaklodingen is 400 m\(^2\) (20x20 m). The bottom
Figure 4.2: The chosen boundaries of the calculation area of the entire ebb tidal delta plotted over the erosion/sedimentation map of the area between 1970 and 2012.

reference depth was chosen at NAP -10 m, which is the seaward boundary of the calculation area.

The entire ebb tidal delta was also subdivided into 4 main areas to distinguish the development of the central part with the channels and shoals (figure 4.3, black line), Kwade Hoek (figure 4.3, red line), the foreshore (figure 4.3, blue line) and the Westplaat (figure 4.3, magenta line). The areas are divided into main areas of erosion (foreshore, blue line), sedimentation (Kwade Hoek, red line and the central part, black line) and areas where almost no erosion or sedimentation occurs (Westplaat, magenta line). Just like the sediment volume calculations of the entire area, the sediment volumes of the main areas are calculated to the bottom reference depth of NAP -10 m. This reference depth is also the seaward boundary of the entire area. The same time steps which were also used for the sediment volume calculations of the entire delta are used.
Figure 4.3: The chosen boundaries of the different areas inside the calculation area of the entire ebb tidal delta plotted over the erosion/sedimentation map of the area between 1970 and 2012.

The increase of the sediment volumes relative to 1970 were calculated as follows:

$$\Delta V = V_t - V_{1970}$$  \hspace{2cm} [6]

where $\Delta V$ is the increase in sediment volume (m$^3$) relative to the sediment volume in 1970, $V_t$ is the sediment volume (m$^3$) at a given time step and $V_{1970}$ is the reference sediment volume (m$^3$) in 1970. The distribution of the channels and shoals to the increase in sediment volume of the entire ebb tidal delta is expressed in percentages and is calculated for each time step by the following equation:

$$D = \frac{\Delta V_{\text{channels/shoals}}}{\Delta V_{\text{delta}}} \times 100$$  \hspace{2cm} [7]

where $D$ is the distribution (%) of the channels or shoals relative to the entire ebb tidal delta, $\Delta V_{\text{channels/shoals}}$ is the increase in sediment volume (m$^3$) of the channels or shoals relative to the sediment volume in 1970 and $\Delta V_{\text{delta}}$ is the increase in sediment volume (m$^3$) of the entire ebb tidal delta relative to the sediment volume in 1970. Both $\Delta V_{\text{channels/shoals}}$ and $\Delta V_{\text{delta}}$ are calculated with equation 6. The increase in sediment volume of the shoals relative to 1970 was calculated by the areas above NAP -2.2 m and within the selected calculation area for the entire ebb tidal delta and is based on the sum of the volumes of the channels/shoals as calculated using equation [2]. For the increase of the sediment volume of the channels...
relative to their sediment volume in 1970 this was slightly different, because sedimentation in these morphological units was determined as a decrease in water volume below the reference depth of NAP -5 m (NAP -4.4 m for the Slijkagt). Therefore, for the channels, the absolute value calculated by equation [6] is used to determine the increase in sedimentation.
5. Results

In this chapter, the results of the research are presented. First, the preliminary observations of the development of the morphological units based on the contour line definition are elaborated in section 5.1 to give an overview of the presence of morphological units during the researched time period. The development of the morphological shoal and channel features is presented in section 5.2 and 5.3, respectively.

5.1 Morphological units

In this section the morphological development of the shoals and channels is given based on the bathymetric data and the contour lines.

5.1.1 Shoals

Figure 5.1: Overview of the presence of shoals through time. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new shoal coming from the southwest, V = Supershoal.
In this research the shoals are defined as the areas which are enclosed by the contour lines at NAP -2.2 m. The contour lines plotted over the bathymetric data gives a general observation of the presence of the shoals in this area through time. Appendix 1 gives the bathymetric data with contour lines at NAP -2.2 m. Individual morphological units are indicated with the Roman numerals I-V. When a contour line splits into two segments and reconnects afterwards, the segments are indicated with the characters ‘a’ and ‘b’.

In the period 1964-1986 two shoals are present (I and II) (figure 5.1 a). The largest shoal is the Hinderplaat (I) in the north-western part of the area. In front of the mouth of the former estuary a smaller shoal, the northern part of the Garnalenplaat (II), is present. During this time period the surface area of the shoals above NAP -2.2 m increases. In the period 1986-1989 the contour line of the southern part of the Garnalenplaat (III) is present and indicates that this shoal rose above the reference depth (figure 5.1 b). The Slufter was finished after the bathymetric monitoring of 1986 and is clearly visible in the bathymetry of 1989. In 1992 the southern part of the Garnalenplaat has been split up into two segments (IIla and IIlb) (Appendix 1 figure A1.13), which will be reconnected into one single shoal (III). In the period 1989-1996, solely the shoals I, II and III remain present and the surface area of the shoals increases.

In 1998 a new shoal (IV) is entering the system (figure 5.1 c), coming from the south-west. Shoal IV connects to the Hinderplaat (I) in 2001, which is the start of the formation of a large Supershoal (V). To this Supershoal the other shoals will connect one by one. In 2003 the northern part of the Garnalenplaat (II) attaches to the Supershoal and eventually the southern part of the Garnalenplaat (III) will merge the Supershoal in 2009. In 2012 the Supershoal is separated in two segments Va and Vb (figure 5.1 d), due to a breakthrough at NAP -2.2 m by a new west-east oriented channel, which probably caused the splitting of the Hinderplaat (Ia and Ib) in 1999 as well.
5.1.2 Channels

Figure 5.2: Overview of the presence of the channels through time. I = Rak van Scheelhoek, II = channel II, III = Bokkegat, IV = Gat van de Hawk (until 1986) / Hindergat (since 1986), V = Slijkgat and VI = new breakthrough channel. Note that the Slijkgat is presented by the NAP -5 m in this figure. In the calculations the reference depth NAP -4.4 m is used for this channel.

The channels are defined as the areas which are enclosed by the NAP -5 m contour lines. The Slijkgat (V) is an exception and is defined by the contour line at NAP -4.4 m. Just like the case with the shoals, the bathymetric data gives an overview of the presence of the channels in the Haringvliet delta area through time. The bathymetric data with the channel contour lines is present in Appendix 3. Individual morphological units are indicated with the Roman numerals (I-VI). When a contour line splits into two segments and reconnects afterwards, the segments are indicated with the characters ‘a’ and ‘b’.

In 1970 all channels are connected to each other to form a large branching channel system. This large branching system contains the Rak van Scheelhoek (I), channel II, Bokkegat (III), Gat van de Hawk (later channel IV) and the Slijkgat (V) (figure 5.2 a). Originating from this large branching channel system, smaller segments are aborted one by one by shallow infilling areas. These infilling areas are located at the point of bifurcation of the channels. First a small part (channel II) becomes isolated in 1972, which already has disappeared at
the NAP -5 m reference depth in 1976. The Bokkegat (III) leaves the large channel system in 1972 as well and its surface area continues to decrease up to and including the year 2001. In the year 2003 the Bokkegat cannot be recognized by the NAP -5 m depth contour line anymore.

In 1976 the Gat van de Hawk (IV) is aborted from the large channel (I) and will be located in the northern part of the area. After the construction of the Slufter the channel has been excavated under the Slufter and is now called the Hindergat (IV). This channel is still present in 2012. The Rak van Scheelhoek (I) does no longer exist in the year 1992.

The Slijkgat (V) is present throughout the entire researched time period. A new channel (VI) has been formed since 2001 and still exists in 2012 (figure 5.2 d). This channel divides the Supershoal into two parts.

5.2 Morphological characteristics of the shoals

The morphological development of the shoals is determined by the surface area, sediment volume and average height above the reference depth of NAP -2.2 m. Additional, the displacement of the centroid of the polygons is used as a morphological feature. Below the development of these morphological features through time are discussed for the individual shoals.

5.2.1 Surface area

The development of the surface area of the shoals is shown in figure 5.3. An overview of the rate of changing surface area is given in table 5.1. Almost all surface areas of the shoals show an increase in time. However, the surface area of the Hinderplaat (I, figure 5.3, blue line) decreases by halve between 1986 and 1989 from about $7 \times 10^6$ m$^2$ to $3.5 \times 10^6$ m$^2$ (rate $1.2 \times 10^6$ m$^2$ year$^{-1}$). It is not likely that such a large alternation in the surface area occurs under natural conditions and thus might be caused by the influence of human interventions. Actually, the Slufter was built in this period and covered a large part of the northern Hinderplaat. This causes a decrease in surface area and sediment volume, which will be discussed in section 6.1.1.

After 1989 the surface area of the Hinderplaat seems to stabilize around $4 \times 10^6$ m$^2$ and splits up in 1999 into two segments of about $2 \times 10^6$ m$^2$ for the northern part and $2.5 \times 10^6$ m$^2$ for the southern part. When the surface area of these two areas are combined it will result in a total surface area of about $4.5 \times 10^6$ m$^2$, which is a small increase compared to the previous year 1998. Previous to the construction of the dam, there is already a fast increase in the surface area of the Hinderplaat. Between 1964 and 1968 the surface area almost doubles from...
approximately $2.75 \times 10^6 \text{ m}^2$ to $5.25 \times 10^6 \text{ m}^2$ (rate $0.63 \times 10^6 \text{ m}^2 \text{ year}^{-1}$). Just like in the period 1986-1989, this is a vast increase for such a small time period. Possible human interferences, such as the construction of the Maasvlakte 1 or the construction of the Haringvliet dam itself, which might have played a role in this will be discussed in section 6.1.1. After this large increase before 1970, between 1968 and 1980 the surface area of the Hinderplaat was slightly increasing from approximately $5.25 \times 10^6 \text{ m}^2$ to $7 \times 10^6 \text{ m}^2$ (rate $0.15 \times 10^6 \text{ m}^2 \text{ year}^{-1}$) and remained stable until 1986 at this latter amount.

The northern part of the Garnalenplaat (II, figure 5.3, red line) shows an overall increase of the surface area from $0.6 \times 10^6 \text{ m}^2$ in 1964 up to $2.75 \times 10^6 \text{ m}^2$ in 2001. The rate of increase in surface area doubles from $0.04 \times 10^6 \text{ m}^2 \text{ year}^{-1}$ in the period 1968-1986 to $0.08 \times 10^6 \text{ m}^2 \text{ year}^{-1}$ in the period 1986-2001. In 1989 the southern part of the Garnalenplaat (III, figure 5.3, green line) rose above NAP -2.2 m with a surface area of $0.6 \times 10^6 \text{ m}^2$ and increased up to approximately $2.5 \times 10^6 \text{ m}^2$ in the year 2006.

Both the duplication in the rate of surface increase of the northern part of the Garnalenplaat and the fact that the southern part of the Garnalenplaat suddenly rose above NAP -2.2 m after 1986 is remarkable.

A fast introduction of the new shoal coming from the south-west (IV, figure 5.3, magenta line) can be recognized during the years 1998 and 1999 where it increases in surface area with $0.9 \times 10^6 \text{ m}^2$ in one year, before it attaches to the Hinderplaat. Eventually all shoals end up in one single Supershoal (V, figure 5.3, grey line), which shows an enormous increase in surface area from $6 \times 10^6 \text{ m}^2$ in 2001 up to $16 \times 10^6 \text{ m}^2$ in 2012 (rate $0.9 \times 10^6 \text{ m}^2 \text{ year}^{-1}$). The increase between 2003 and 2003 is partly caused due to the fact that the northern part of the Garnalenplaat (II) merged with the Hinderplaat (V) and the new shoal (IV). However the increase of the Supershoal is $4 \times 10^6 \text{ m}^2$ whereas the surface of the northern Garnalenplaat (II) is about $2.75 \times 10^6 \text{ m}^2$ in 2001. So the surface area of the Supershoal (V) in the period 2003 - 2006 has been increasing in its totality as well. The increase between 2006 and 2009 is mainly induced by the connection of the southern part of the Garnalenplaat (III) to the Supershoal (V). After 2009 until 2012 the Supershoal is divided into two segments. The northern part (Va) contains a surface area of $2.5 \times 10^6 \text{ m}^2$ and the southern part is $1.3 \times 10^7 \text{ m}^2$.

The total rate of increase between 2009 and 2012 is therefore $1 \times 10^6 \text{ m}^2 \text{ year}^{-1}$, which is very fast. Because this increase does not seem to occur naturally, the reasons why there is such a fast increase will be discussed in section 6.1.3.

The sum of all shoals above NAP -2.2 m is represented by the black line in figure 5.3. In the period 1964-1990 the pattern of increase of surface area seems to be dominated by the character of the Hinderplaat (I), mainly due to the fact that the rate of increase of the northern Garnalenplaat (II) is very small ($0.4 \times 10^6 \text{ m}^2 \text{ year}^{-1}$) while the Hinderplaat shows a vast increase in this time period. After 1990 the total surface area increases very fast mainly.
caused by the growth of the southern part of the Garnalenplaat (III) and the new shoal coming from the south-west (IV). However, the final increase (2009 – 2012) is very fast and is equal to the increase of the Supershoal, because all shoals have ended up in the Supershoal.

Figure 5.3: Surface area of the individual shoals and the summation of all shoals (thick black line). I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new shoal coming from the southwest, V = Supershoal.

Table 5.1: Rate of increase (green) and decrease (red) of the surface area of the shoals above NAP -2.2 m. Rates are given in $m^2 \cdot year^{-1}$.

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<tbody>
<tr>
<td>Hinderplaat (I)</td>
<td>+0.63·10^6</td>
<td>+0.15·10^6</td>
<td>Stable</td>
<td>-1.2·10^6</td>
<td>Stable (until 1998)</td>
</tr>
<tr>
<td>Northern Garnalenplaat (II)</td>
<td>+0.04·10^6</td>
<td>+0.04·10^6</td>
<td>+0.04·10^6</td>
<td>+0.08·10^6</td>
<td>+0.08·10^6 (until 2001)</td>
</tr>
<tr>
<td>Southern Garnalenplaat (III)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0.11·10^6 (until 2003)</td>
</tr>
<tr>
<td>New Shoal (IV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0.9·10^6 (1998 – 1999)</td>
</tr>
<tr>
<td>Supershoal (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0.9·10^6 (2001 – 2012)</td>
</tr>
</tbody>
</table>
5.2.2 Sediment volume

The development of the sediment volume of the shoals is shown in figure 5.4. An overview of the rate of changing sediment volume is given in table 5.2. The patterns of sediment volume through time are very similar to the patterns in surface area, but with some subtle differences. An exception is the Hinderplaat (I, figure 5.4, blue line). The Hinderplaat shows a vast increase in sediment volume in the period 1964-1980, from approximately $1.5 \times 10^6$ m$^3$ to $7 \times 10^6$ m$^3$ which is a sedimentation rate of $0.3 \times 10^6$ m$^3$ year$^{-1}$. After 1980 the sediment volume of the Hinderplaat decreases to approximately $3.25 \times 10^6$ m$^3$ in 1998 with an erosion rate of $-0.2 \times 10^6$ m$^3$ year$^{-1}$. Just like the surface area there is a drop in sediment volume between 1986 and 1989. As it was mentioned in section 5.2.1, the Slufter was built over the northern part of the Hinderplaat in this period, causing a decrease in surface area and sediment volume. This will be discussed in section 6.1.1. In 1989 the Hinderplaat consists of 2 separate parts containing $1.75 \times 10^6$ m$^3$ of sediment in the northern part and $2.5 \times 10^6$ m$^3$ in the southern part. As a result the sediment volume of the Hinderplaat is $4.25 \times 10^6$ m$^3$ in total in 1999.

On average the sediment volume of the northern part of the Garnalenplaat (II, figure 5.4, red line) is increasing in a way similar to its surface area. It remains quite stable until 1986, where after the sedimentation rate increases. However, in the period 1976-1986, the sediment volumes drop slightly and remain stable at this value. The southern part of the Garnalenplaat (III, figure 5.4, green line) only increases from approximately $0.25 \times 10^6$ m$^3$ in 1989 to about $1.75 \times 10^6$ m$^3$ in 2006 which is a sedimentation rate of $0.09 \times 10^6$ m$^3$ year$^{-1}$.

The volume of the new shoal coming from the south-west (IV, figure 5.4, magenta line) increases with $0.25 \times 10^6$ m$^3$ in one year.

Just like the surface area, the increase of the volume of the Supershoal (V, figure 5.4, grey line) is very large, from $4.5 \times 10^6$ m$^3$ in 2001 to $12.75 \times 10^6$ m$^3$ in 2012. The addition of the northern part of the Garnalenplaat (II) to the Supershoal between 2001 and 2003 is the main cause for the increase in sediment volume, whereas for the period 2006-2009 the addition of the southern part of the Garnalenplaat (III) is a major factor. The sedimentation rate between 2009 and 2012 is even larger and may be caused by the construction of the Maasvlakte 2, which will be discussed in section 6.1.3.

The sum of sediment volume of all shoals above NAP -2.2 m is shown by the black line in figure 5.4. Until 1980 the pattern of the total sediment volume is dominated by the pattern of the sediment volume of the Hinderplaat (I), it shows a trend of sedimentation. Between 1980 and 1998 a slightly erosional trend is present, which is the result of a decreasing sediment volume of the Hinderplaat (I) and increasing sediment volumes of the northern and southern parts of the Garnalenplaat (II and III). From 1998 up to 2012 the total sediment volume increases again as a result of the formation of the Supershoal (V).
Morphological development of the Haringvliet ebb tidal delta since 1970

January, 2014

Rijkswaterstaat, Deltares and Universiteit Utrecht

Figure 5.4: Sediment volume of the individual shoals and the summation of all shoals (thick black line). I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new shoal coming from the southwest, V = Supershoal.

Table 5.2: Rate of increase (green) and decrease (red) of the surface area of the shoals above NAP -2.2 m. Rates are given in m$^3$ year$^{-1}$.

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<tbody>
<tr>
<td>Hinderplaat (I)</td>
<td>+ 0.3·10$^6$</td>
<td>+ 0.3·10$^6$</td>
<td>- 0.2·10$^6$</td>
<td>- 0.4·10$^6$</td>
<td>- 0.2·10$^6$ (until 1998)</td>
</tr>
<tr>
<td>Northern Garnalenplaat (II)</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
<td>+ 0.1·10$^6$</td>
<td>+ 0.1·10$^6$ (until 2001)</td>
</tr>
<tr>
<td>Southern Garnalenplaat (III)</td>
<td></td>
<td></td>
<td></td>
<td>+ 0.09·10$^6$ (until 2006)</td>
<td></td>
</tr>
<tr>
<td>New Shoal (IV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 0.25·10$^6$ (1998 – 1999)</td>
</tr>
<tr>
<td>Supershoal (V)</td>
<td></td>
<td></td>
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<td></td>
<td>+ 0.75·10$^6$ (2001 – 2012)</td>
</tr>
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</table>

5.2.3 Average height

The average shoal height is represented in figure 5.5. An overview of the rate of changing average shoal height is given in table 5.3. The Hinderplaat (I, figure 5.5, blue line) behaves different compared to the other shoals, as it was observed from the development of the
surface area and sediment volume. In the period 1970-1980, there is a strong increase in average shoal height above NAP -2.2 m. This is the result of a strong increasing sediment volume and less strong increasing surface area of the Hinderplaat. After 1980 there is a small period of decreasing average height of about 0.15 m in 4 years. In the period 1986 – 1989, the rate of increase in average shoal height is very large (0.13 m year⁻¹). This is not solely caused by sedimentation in this area, but likely caused by the Slufter coverage of the northern part of the Hinderplaat, which will be discussed in section 6.1.1. After 1991 the average height decreases again with a rate of about -0.06 m year⁻¹.

Before 1970 the average height of the northern part of the Garnalenplaat (II, figure 5.5, red line) shows an increasing trend of 0.03 m year⁻¹. An opposite trend between 1970 and 1980 compared to the trend of the Hinderplaat can be recognized in the period 1970 - 1980. The average height of the shoal is decreasing with a rate of about -0.05 m year⁻¹. After 1980 an increasing trend is visible of 0.02 m year⁻¹. The southern part of the Garnalenplaat (III, figure 5.5, green line) is increasing with a rate of 0.02 m year⁻¹ between 1989 and 2006. The new shoals coming from the south west (IV, figure 5.5, magenta line) has increased 0.1 m in a year. The Supershoal (V, figure 5.5, grey line) shows a slight sedimentation, with a trend of about 0.1 m year⁻¹. When all shoals are added to each other, the average shoal height increases with a rate of 0.03 m year⁻¹ until 1976. Between 1976 en 1990 on average the trend is slightly increasing, but in the period 1980 - 1998 it is unstable where the average height drops about 0.1 m. After 1990 the average height drops about 0.2 m to become slightly increasing after 2000.
Figure 5.5: Average height of the shoals above NAP -2.2 m and the summation of all shoals (thick black line). I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new shoal coming from the southwest, V = Supershoal.

Table 5.3: Rate of increase (green) and decrease (red) of the average height of the shoals above NAP -2.2 m. Rates are given in m year⁻¹.

<table>
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</thead>
<tbody>
<tr>
<td>Hinderplaat (I)</td>
<td>+ 0.04</td>
<td>+ 0.04</td>
<td>- 0.04</td>
<td>+ 0.13</td>
<td>- 0.06</td>
</tr>
<tr>
<td>Northern Garnalenplaat (II)</td>
<td>+ 0.03</td>
<td>- 0.05</td>
<td>+ 0.02</td>
<td>+ 0.02</td>
<td>+ 0.02     (until 2001)</td>
</tr>
<tr>
<td>Southern Garnalenplaat (III)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 0.02     (until 2003)</td>
</tr>
<tr>
<td>New Shoal (IV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 0.1      (1998 – 1999)</td>
</tr>
<tr>
<td>Supershoal (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 0.1      (2001 – 2012)</td>
</tr>
</tbody>
</table>

To make an indication of the vertical distribution of sediment volume of the shoals, the sediment volumes above different reference heights with the same depth interval are shown in figure 5.6. The course of the sediment volume through time is above all reference depths more or less the same. However it can be recognized that the difference between two
different reference depths increases at lower reference depths. Additionally, the difference increases during the latest time periods.

![Sediment volume above different reference depths](image)

Figure 5.6: Sediment volume above different reference depths.

### 5.2.5 Displacement, shape and orientation of the centroids

An overview of the displacement of the centroids of the shoals in the Haringvliet area is represented in figure 5.7. It is important to mention that the displacement of a centroid can be caused by two factors: the displacement of a single morphological unit (polygon) and non-uniform growth at the edges or deformation of the surface area of the morphological unit.
Figure 5.7: Displacement of the centroids of the shoals I-V. The earliest centroid of a shoal is marked with a name label and the year wherein the shoal was first present. The arrows do not represent the exact magnitude and displacement of the centroids, but give an indication of the average displacement through time. The black depth contour lines are the NAP -2.2 m contour lines of 1970 to give a spatial reference for the centroids. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new channel coming from the southwest, V = Supershoal.

The centroid of the Hinderplaat (figure 5.7, shoal I), first migrates to the north-west where it stays more or less at the same location for several years. Then there is a sudden movement straight to the south, where it remains more or less at the same location again. The displacement of the centroid of the Hinderplaat is shown in figure 5.8 in more detail. Before the closure of the Haringvliet dam, the Hinderplaat was situated relatively landward (1964). After the construction of the dam, the centroid shifted in seaward direction to the north-west (1970 and 1986). Additionally, the shape and orientation of the Hinderplaat changed. Between 1964 and 1970 the orientation changed from northwest-southeast to northeast-southwest and its shape smoothened, which will be discussed in section 6.1.1. In the period 1970-1986 the centroid does not have a significant displacement, but the shape of the Hinderplaat became more elongated compared to the situation in 1970. After 1986 there is a
large shift of the centroid to the south which is visible in the situation of 1989. The cause of this shift will be discussed in section 6.1.1. In 1999 the Hinderplaat has been split up into two parts and thus contains two centroids, one towards the north and one towards the south. In the period 1970-1999 the orientation of the Hinderplaat turns from northeast-southwest to north-south.

Figure 5.8: Centroid displacement of the Hinderplaat through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

The displacement of the centroid of the northern Garnalenplaat (figure 5.7, shoal II), which is the northern part of the Garnalenplaat, moves towards the north whereby it stays more or less stable. The displacement of the northern part of the Garnalenplaat is shown in figure 5.9 in more detail. In 1964 the northern Garnalenplaat is a west-east oriented elongated shoal. In 1970 its centroid is situated about 730 m northward of the situation in 1964. This is a displacement of about 120 m year\(^{-1}\). The shoal also contains a northwest-southeast oriented extension at its eastward edge. In the period 1970-1986 the centroid moves with an annual average velocity of 19 m year\(^{-1}\) to the north, where it remains quite stable until 1999. Between 1989 and 1999 the centroid shifts again to the north with an average annual velocity of 23 m year\(^{-1}\). This latter displacement is mainly caused by the extension of the
northern Garnalenplaat to the north, because the southern edge of the shoal is more or less fixed since 1989 due to the presence of a channel south of the Hinderplaat. Thus, the displacement of the centroid can also be caused by a change in the shape of the shoal. Actually, the displacement of the centroid may have two different causes (figure 5.10):

1. The morphological unit (polygon) has been displaced in total and did not change much of its shape. The morphological unit may have increased or decreased in volume, but uniform around the entire unit.
2. The shape of the morphological feature may have changed.

Figure 5.9: Centroid displacement of the northern Garnalenplaat through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.
Figure 5.10: Centroid displacement due to the displacement of the centroid itself (1) or due to a change in shape (2).

The displacement of the southern part of the Garnalenplaat (figure 5.7, shoal III), first moves in western direction where after it shifts somewhat to the north-east. The displacement of the southern part of the Garnalenplaat is shown in figure 5.11 in more detail. In the period 1989-1992 the shoal splits up into two parts and so does the centroid. Between 1989 and 1996 the centroid of the southern Garnalenplaat moves approximately 1 km towards the west, which is a rate of about 140 m year\(^{-1}\). The displacement is mainly caused by the extension of the shoal in westward direction. After 1996 the centroid moves in north-eastern direction with a rate of about 75 m year\(^{-1}\) in the period 1996-2003 and a rate of 120 m year\(^{-1}\) between 2003 and 2006. This kind of displacement is also caused by an extension of the shoal, but towards the north-east direction.
Figure 5.11: Centroid displacement of the southern Garnalenplaat through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

The displacement of the centroid of Shoal IV (figure 5.7) is directed to the north-east. Only two time intervals are present before it attaches to the Hinderplaat to form the Supershoal, but it can be observed that the centroid of Shoal IV does move towards the Hinderplaat. The magnitude of displacement is approximately 610 m in one year. This is mainly caused by the growth of the surface area towards the north-east (figure 5.12).
Figure 5.12: Centroid displacement of shoal IV through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

The connection of Shoal IV and the Hinderplaat in 2001 results in one single centroid, which is the centroid of the Supershoal (figure 5.7, shoal V). The centroid then moves towards the south-east, which is caused by the attachment of the northern Garnalenplaat between 2001 and 2003 and the southern Garnalenplaat between 2006 and 2009. This can also be seen in the detailed figure of the Supershoal (figure 5.13). Because the displacement of the centroid is caused by the attachment of such large shoals like the northern and southern Garnalenplaat, the magnitude is very large. The annual average velocity due to the connection of the northern Garnalenplaat (2001-2003) is 400 m year\(^{-1}\) and for the southern Garnalenplaat (2003-2009) the rate is 90 m year\(^{-1}\).

On average, all shoals eventually move towards the centre of the former Haringvliet ebb tidal delta.
Figure 5.13: Centroid displacement of the Supershoal (V) through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.
5.3 Morphological features of the channels

The morphological development of the channels is determined by the surface area, water volume and average water depth below the reference depth of NAP -5 m and the displacement of the centroid of the polygon. Below the development of these morphological features through time are discussed for the individual channels.

5.3.1 Surface area

The surface area of the channels is plotted in figure 5.1. An overview of the rate of change in surface area is given in table 5.4. The channels are divided in large (upper panel) and small (lower panel) channels. This manner of display is chosen because the surface area of the large channels is an order of magnitude larger compared to the small channels, which makes the small channels invisible when plotting them in the same figure. From this it already can be concluded that there is a large difference in the dimensions of the channels.

Note that the reference depth of the Slijkgat was chosen at a shallower depth (NAP -4.4 m) compared to the other channels (NAP -5 m). The surface area of the Slijkgat is relatively large compared to the surface area of the other channels. For this reason only increasing and decreasing trends can be compared.

The surface areas of the Rak van Scheelhoek (I, figure 5.1, blue line) and Slijkgat (V, figure 5.1, grey line) are plotted in the upper panel of figure 5.1. Both channels show a decreasing trend in surface area between 1970 and 1990 where the rate of the Slijkgat (-2.5\times10^5 m^2 year^{-1}) is smaller than the rate of the Rak van Scheelhoek (-3.75\times10^5 m^2 year^{-1}). After 1991 the Rak van Scheelhoek has disappeared whereas the Slijkgat still exists and sort of stabilizes around a surface area of 5\times10^6 m^2 year^{-1}, which will be discussed in section 6.2.4.

Channel II (figure 5.1, red line) is only visible below NAP -5 m in 1970 and 1972 where after it disappears at this reference depth. The surface area of the Bokkegat (III, figure 5.1, green line) shows a decreasing trend between 1970 and 1980 with a rate of -2\times10^5 m^2 year^{-1}. Thereafter the surface area of this channel sort of stabilizes around 2.5\times10^5 m^2. This continues until 2001, because in 2003 the Bokkegat is not visible anymore at the reference depth of NAP -5 m.

The surface areas of the Hindergat (IV, figure 5.1, magenta line) are quite stable around 2.5\times10^5 m^2. This is also valid for the new channel (VI, figure 5.1, cyan line) which breaks through the Hinderplaat originating in 2001, but at a smaller magnitude of surface area.

When the surface areas of the channels are added to each other the decreasing trend until 1990 is visible and stabilization thereafter. However, because there is a division in large and
small channels, the summation trend is only representative for the large channels while the small channels are omitted. The period between 1989 and 2001 is represented by a dotted line because some of the data of the Slijkgat is missing and thus the total surface area of the channels cannot be calculated for this time period.

Figure 5.14: Surface area of the individual channels and the summation of all channels (thick black line). The largest channels are plotted in the upper panel and the smallest channels in the lower panel. I = Rak van Scheelhoek, II = channel II, III = Bokkegat, IV = Gat van de Hawk / Hindergat, V = Slijkgat, VI = new breakthrough channel. Note that all channels are referenced to the NAP -5 m contour depth except for the Slijkgat (V), which is referenced to the NAP -4.4 m contour depth.

Table 5.4: Rate of increase (green) and decrease (red) of the surface area of the channels below NAP -4.4 m (Slijkgat NAP -5 m). Rates are given in m² year⁻¹.

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</thead>
<tbody>
<tr>
<td>Rak van Scheelhoek (I)</td>
<td>-3.75·10⁵</td>
<td>-3.75·10⁵</td>
<td>-3.75·10⁵</td>
<td>-3.75·10⁵ (until 1991)</td>
</tr>
<tr>
<td>Bokkegat (III)</td>
<td>-2.1·10⁵</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable (until 2001)</td>
</tr>
<tr>
<td>Gat van de Hawk / Hindergat (IV)</td>
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<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
</tr>
<tr>
<td>Slijkgat (V)</td>
<td>-2.5·10⁵</td>
<td>-2.5·10⁵</td>
<td>-2.5·10⁵</td>
<td>-2.5·10⁵ (until 1990)</td>
</tr>
</tbody>
</table>
5.3.2 Water volume

The water volume of the channels is plotted in figure 5.15. An overview of the rate of change in water volume is given in table 5.5. Just like the case of the channel surface area, the channels are divided in large (upper panel) and small (lower panel) channels. It also has to be noted that for the water volume the reference depth of the Slijkgat was chosen at a shallower depth (NAP -4.4 m) compared to the other channels (NAP -5 m) as well. So the water volume of the Slijkgat is relatively large when comparing it to the water volume of the other channels. For this reason only increasing and decreasing trends can be compared between channels.

The trends in water volume of the channels show similar patterns compared to the surface area of the channels. The Rak van Scheelhoek (I, figure 5.15, blue line) and Slijkgat (V, figure 5.15, grey line) decrease towards 1990. Thereafter the Rak van Scheelhoek disappears after 1991. The Slijkgat is increasing in water volume towards 2001 and thereafter it decreases again. This will be discussed in section 6.2.4.

Like the surface area, channel II (figure 5.15, red line) is only visible in 1970 and 1972 with a decreasing trend, where after it disappears.

The water volume of the Bokkegat (III, figure 5.15, green line) decreases between 1970 and 1980. Thereafter it stabilizes near the zero value showing an increase after 1986 with a maximum in 1996. The reason for this will be discussed in section 6.2.2. After this maximum the water volume ceases to the zero value where the channel disappears at the NAP -5 m reference depth after 2001.

The water volume of the Hindergat (IV, figure 5.15, magenta line) is showing a disturbance after 1986 where the water volume of the channel increases and reaches its maximum in 1990. The reason for this might be the fact that in 1986 the Hindergat was excavated by humans and therefore the volume of the channel has to adapt to the hydrodynamics in the area. This will be discussed in section 6.2.3. The new breakthrough channel (VI, figure 5.15, cyan line), existing since 2001, increases in water volume.
Figure 5.1: Water volume of the individual channels and the summation of all channels (thick black line). The largest channels are plotted in the upper panel and the smallest channels in the lower panel. I = Rak van Scheelhoek, II = channel II, III = Bokkegat, IV = Gat van de Hawk / Hindergat, V = Slijkgat, VI = new breakthrough channel. Note that all channels are referenced to the NAP -5 m contour depth except for the Slijkgat (V), which is referenced to the NAP -4.4 m contour depth.

Table 5.5: Rate of increase (green) and decrease (red) of the water volume of the channels below NAP -4.4 m (Slijkgat NAP -5 m). Rates are given in m$^3$ year$^{-1}$.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rak van Scheelhoek (I)</td>
<td>-10$\cdot$10$^5$</td>
<td>-10$\cdot$10$^5$</td>
<td>Stable</td>
<td>Stable</td>
</tr>
<tr>
<td>Bokkegat (III)</td>
<td>-1.2$\cdot$10$^3$</td>
<td>Stable</td>
<td>+0.15$\cdot$10$^5$</td>
<td>-0.3$\cdot$10$^5$ (1996 – 2001)</td>
</tr>
<tr>
<td>Gat van de Hawk / Hindergat (IV)</td>
<td>Stable</td>
<td>Stable</td>
<td>+0.5$\cdot$10$^5$</td>
<td>-0.09$\cdot$10$^5$</td>
</tr>
<tr>
<td>Slijkgat (V)</td>
<td>-8$\cdot$10$^5$</td>
<td>-8$\cdot$10$^5$</td>
<td>-8$\cdot$10$^5$</td>
<td>+3$\cdot$10$^5$ (until 2001) -3.5$\cdot$10$^5$ (2001 – 2012)</td>
</tr>
</tbody>
</table>
5.3.3 Average water depth

The average water depth relative to the reference depth is represented in figure 5.16. An overview of the rate of change in average water depth is given in table 5.6. It is clearly visible that the average water depth of the Rak van Scheelhoek (I, figure 5.16, blue line) is decreasing until the channel disappears after 1991. This is also valid for channel II (figure 5.16, red line), which disappears after 1972.

The average water depth of the Bokkegat (III, figure 5.16, green line) decreases until 1986. Thereafter the average depth increases until 1992 (discussion in section 6.2.2), after 1996 it decreases again. After 2001 the Bokkegat has been filled in up to the reference level of NAP -5 m.

The average water depth of the Hindergat (IV, figure 5.16, magenta line) is increasing until 1990, with a strong rate increase between 1986 and 1989. Because the Hindergat has been excavated south of the Slufter in this period, the strong increasing water depth of the Hindergat after 1986 will be discussed in section 6.2.3. After 1990 the water volume of the Hindergat decreases with a large rate just after 1990 and after 2006, compared to the period between 1992 and 2006.

The average water depth of the Slijkgat (V, figure 5.16, grey line) decreases until 1989. Thereafter the average water depth increases with a peak in the year 2001. After 2001 the water volume of the Slijkgat decreases again. Because the Slijkgat has been frequently dredged, the development of the Slijkgat will be discussed in section 6.2.4.

The new channel which divides the Hinderplaat into two segments (VI, figure 5.16, cyan line) develops in 2001 at the reference depth of NAP -5 m. In two years the average water depth shows a large increase, where after the water volume of the channel seems to stabilize.

The pattern of the total average water depth (figure 5.16, thick black line) is comparable to the pattern of the Slijkgat (V), this is mainly due to the fact that the reference depth of the Slijkgat has been chosen at a shallower water depth compared to the other channels. Because of this reason the Slijkgat has relatively large dimensions and is thus more pronounced in the total average water depth.
Figure 5.16: Average water depth of the individual channels and the summation of all channels (thick black line). I = Rak van Scheelhoek, II = channel II, III = Bokkegat, IV = Gat van de Hawk / Hindergat, V = Slijkgat, VI = new breakthrough channel. Note that all channels are referenced to the NAP -5 m contour depth except for the Slijkgat (V), which is referenced to the NAP -4.4 m contour depth.

Table 5.6: Rate of increase (green) and decrease (red) of the average water depth of the channels below NAP -4.4 m (Slijkgat NAP -5 m). Rates are given in m year\(^{-1}\).

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Rak van Scheelhoek (I)</td>
<td>-0.08</td>
<td>-0.08</td>
<td>-0.08</td>
<td>-0.08 (until 1991)</td>
</tr>
<tr>
<td>Bokkegat (III)</td>
<td>-0.04</td>
<td>Stable</td>
<td>+0.08</td>
<td>Variable</td>
</tr>
<tr>
<td>Gat van de Hawk / Hindergat (IV)</td>
<td>+0.13</td>
<td>+0.02</td>
<td>+0.54</td>
<td>Variable</td>
</tr>
<tr>
<td>Slijkgat (V)</td>
<td>-0.07</td>
<td>Stable</td>
<td>-0.15</td>
<td>+0.05 (until 2001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.02 (2001 – 2012)</td>
</tr>
</tbody>
</table>


### 5.3.4 Displacement of the centroids

An overview of the displacement of the centroids of the channels in the Haringvliet area is represented in figure 5.17.

![Figure 5.17](image)

Figure 5.17: Displacement of the centroids of the channels I-VI. The earliest centroid of a channel is marked with a name label and the year wherein the channel was first present. The arrows do not represent the exact magnitude and displacement of the centroids, but give an indication of the average displacement through time. The black depth contour lines are the NAP -2.2 m contour lines of 1970 to give a spatial reference for the centroids. I = Rak van Scheelhoek, II = channel II, III = Bokkegat, IV = Gat van de Hawk / Hindergat, V = Slijkgat, VI = new breakthrough channel.

The centroids of the Rak van Scheelhoek (figure 5.17, channel I) move from the northwest in southeast direction with a small shift to the east in between. A detailed migration of the centroid of the Rak van Scheelhoek is presented in figure 5.18. In the period 1970 – 1976, the centroid of the Rak van Scheelhoek migrates in south-east direction, mainly caused by a decrease in surface area of the polygon in the northern part of the channel. This is caused by the abortion of the northern part of the channel (Gat van de Hawk (IV), after 1986 Hindergat). The southern part of the channel stays fixed at its location. In the period 1976 – 1984 the centroid displaces towards the east because the south-western side of the channel...
has been reduced and thus the surface area of the Rak van Scheelhoek has decreased. After 1984, the surface area of the Rak van Scheelhoek keeps on decreasing, especially in the northern part, causing a migration of the centroid towards the south. After 1991 the

![Diagram of centroid displacement](image)

Figure 5.18: Centroid displacement of the Rak van Scheelhoek (I) through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

channel is totally filled in with sediment under the reference depth of NAP -5 m and has disappeared.

Channel II (figure 5.17, channel II) is only visible in 1970 and 1972 below NAP -5 m and migrates in westward direction during this time period. In figure 5.19 details containing the contour lines of the channel are shown and it can be seen that the westward migration of the centroid is caused by a decrease in surface area of the eastern part of the channel.
Figure 5.19: Centroid displacement of Channel II through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

The centroid of the Bokkegat (figure 5.17, channel III) moves into south-southeast direction containing 3 periods with quite a stable position where in between the centroid of the channel shifts over large distances. Figure 5.20 shows a more detailed migration of the Bokkegat. Between 1970 and 1980 the displacement of the centroid is not that large. However, showing the contour lines, the decrease in surface area is significant in this period. Due to the uniform infill around the edges of the channel, the centroid stays more or less at the same location. In the years after 1980 the shape and surface area of the Bokkegat do not change significant, but the channel is migrating into south-southeast direction. This is clearly visible using the centroids of the polygons of the Bokkegat. In 2001 the surface area has clearly decreased, where after the Bokkegat has totally filled in under the reference depth NAP -5 m and disappears.
Figure 5.20: Centroid displacement of the Bokkegat (III) through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

The centroid of the Hindergat (figure 5.17, channel IV) first moves in northwest direction, where after it suddenly turns towards the southwest where it remains at a quite stable position. The detailed representation of the migration of the Hindergat is shown in figure 5.21. When the centroids are displayed with the contour lines of the Hindergat, the displacement of the centroid can be subdivided into two stages. In the period 1976 – 1980, the migration is caused by the infill of the southern part of the channel. Between 1980 and 1986 the surface area and shape of the polygon do not change significantly and the centroid of the Hindergat migrates in southwest direction due to the displacement of the polygon itself. The second stage is that the centroid of the channel makes a large shift towards the southwest and the polygon of the polygon of the channel in its totality does this as well. The large shift will be explained in section 6.2.3 of the discussion. Then, in the period 1989 – 2006, the centroid of the channel is stays more or less around this location. After 2006 the Hindergat is not recognizable anymore below the reference depth of NAP -5 m.
Figure 5.20: Centroid displacement of the Hindergat (IV) through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

The centroid of the Slijkgat (figure 5.17, channel V) first migrates towards the east and then moves back to the west, slightly towards the north. A detailed overview of the migration of the Slijkgat is shown in figure 5.22. In the period 1970 – 1986, the centroid of the Slijkgat migrates towards the east. At its eastward end the borders at NAP – 5 m are quite fixed whereas at the western part of the channel, the polygon is decreasing in its surface area which caused the displacement of the centroid. Between 1986 and 1989, the centroid moves back towards the west in between the centroids of 1970 and 1986. This is mainly caused by the seaward extension and connection of the Slijkgat to the sea below NAP -4.4 m. In 2012 the centroid of the channel is situated slightly to the north and it seems that the reason for this is that the outer bend of the channel is extending to the north. Figure 5.22 shows that the boundaries of the polygon of the Slijkgat do not tightly connect to the Haringvliet dam after 1986. This is caused due to the absence of data near the dam, causing a non-closed contour line (Appendix 3). Because data is missing near the dam, the calculations of the water volume of the Slijkgat are slightly underestimated. Additionally, the centroid of the Slijkgat would be located slightly more towards the south east.
Figure 5.2: Centroid displacement of the Slijkgat (V) through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

In 2001 a new channel (figure 5.17, channel VI) reaches below the reference depth of NAP -5 m. The centroid of this channel migrates in eastern direction. Details of the migration of channel VI are represented in figure 5.23. Between 2001 and 2001 the centroid migrates towards the east mainly due to the extension of the channel in eastward direction. In 2006 the channel exists of two segments of which the new part is situated eastward of the original channel. In 2009 and 2012 it is a west-east oriented elongated channel.
Figure 5.23: Centroid displacement of the new channel which divides the Hinderplaat into two segments (VI) through time. The coloured centroids with the depth contour lines indicate the time steps with significant changes. The time steps where no significant changes occur are indicated with small blue crosses.

5.4 Sediment volume changes of the entire ebb tidal delta
The sediment volumes of the entire ebb tidal delta above the reference depth of NAP -10 m are shown in figure 5.24. Between 1970 and 1980 the sediment volume of the entire ebb delta increases vast, with a sedimentation rate of about 3.6\times10^6 m^3 year^{-1} (table 5.7). After 1980 until 1989 the sediment volume stays constant at about 5.1\times10^8 m^3. In the period 1992 – 2006 the sediment volume is again stable, but at a higher amount (about 5.2\times10^8 m^3). Between 2009 and 2012 there is again a strong increase in sediment volume. The sedimentation rate is approximately 4.5\times10^6 m^3 year^{-1} in this time period (table 5.7). The increase of sediment volume of the channels (areas below NAP -5 m and for the Slijkgat the area below NAP -4.4 m) relative to 1970 (figure 5.24, blue line) shows a strong increase between 1970 and 1979 (sedimentation rate 2.2\times10^6 m^3 year^{-1}). Thereafter the increase in sediment volume decreases and remains quite stable around 2.5\times10^7 m^3.
The shoals (areas above NAP -2.2 m) first show a quite stable trend from 1970 until 1998. The sediment volume increases only slightly in this period. The fastest sedimentation rate occurs between 1970 and 1980. Thereafter the sediment volume is quite stable where after the sedimentation rate increases.

The distributions of the shoals and channels on the increase of sediment volume of the entire ebb tidal delta are shown in figure 5.25. The channels below the reference depth of NAP -5 m (and NAP -4.4 m for the Slijkgat) (figure 5.25, blue line) distribute the most on the sedimentation of the entire ebb tidal delta. Until 1970 there is a large peak in the distribution of the channels in the sediment increase of the entire ebb tidal delta relative to the sediment volume in 1970. After 1980 the distribution of the channels shows a slightly decreasing trend while the distribution varies between 40 and 70%. Because the sediment volumes of the Slijkgat are calculated to a different reference depth than the reference depth of the other channels, the distribution of the increase in sediment volume relative to the sediment volume...
in 1970 of the Slijkgat and the other channels are displayed separately (figure 5.25, grey and cyan lines, respectively). In figure 5.25 it can be seen that in the period 1970 – 1980, the distributions of the Slijkgat and the other channels in the sediment volume changes of entire ebb tidal delta are contrary. The influence of the Slijkgat increases in this period, while the distribution in sediment volume increase of the other channels decreases. After 1980 the distribution of the channels becomes slightly decreasing around 25 and 35% for the Slijkgat and the other channels, respectively.

The distribution of sediment volumes of the shoals above NAP -2.2 m (figure 5.25, red line) is different compared to the channels. First, it can be recognized that the distribution is smaller compared to the distribution of the channels and second there are also some differences in the trends. In the period 1970 – 1980 the distribution of the shoals shows a decreasing trend. Thereafter until 1998 the distribution remains stable around 5%. Finally the distribution of the sediment volume increase in the increase in sediment volume of the entire delta is increasing in the period 1998 – 2012.

Figure 5.25: Distribution of the sediment volume increase of the shoals, channels and Slijkgat on the sediment volume increase of the total ebb tidal delta in %.
In figure 5.26 the sediment volume change relative to 1970 of the former ebb tidal delta is subdivided into 4 main areas (figure 4.3): the central part (black line, containing the channels and shoals), the Kwade Hoek (red line), foreshore (blue line) and the Westplaat (magenta line). Both the central part and the Kwade Hoek do increase in sediment volume, relative to 1970. The increase of the Kwade Hoek is relatively large compared to the increase of the central part, because the total area of the central part is much larger compared to the surface area of the Kwade Hoek and the increase in sediment volume of the Kwade Hoek is 25 to 40% of the increase in sediment volume of the central part. The sediment volume of the Westplaat does not change much relative to the sediment volume of the Westplaat in 1970. The sediment volume of the foreshore is strongly decreasing compared to the sediment volume of the foreshore in 1970.

If it is assumed that the increase in sediment volume of the Kwade Hoek is caused by the arriving horizontal sand waves combined with the fact that the Westplaat does not change much, it can be assumed that the foreshore is probably the main source for the sediment increase in the central part. In figure 5.27 the increase in sediment volume of the central part (black line) and the foreshore (blue line) are shown again. Additionally, the absolute values of the sediment volume increase of the foreshore (green line) and the difference between the
sediment volumes of the foreshore and the central part (red line) are plotted. If it is assumed that the foreshore only functions as a sediment supply for the central part, the green line indicates the sediment supply of the foreshore to the central part and the red line indicates the sediment volume of the central part which is supplied by other sources than the foreshore. The sediment supply of the foreshore shows an almost linear increasing contribution to the central part, whereas the other sources show another course. The contribution of the other sediment sources increases fast until 1980, where after it slowly decreases.

Figure 5.27: Increase in sediment volume relative to 1970 for the central part (black line) and the foreshore (blue line). An indication of the sediment supply of the foreshore (green line) and other sources (red line) for the central part is given as well.
6. Discussion

6.1 Morphological development of the shoals
In this section the morphological development of the individual shoals will be discussed based on the results described in section 5.2 to answer the research question and test the hypothesis of 1.a. In some cases the research questions and hypotheses 2.a and 3.a can be tested. Initiative answers will be given to the research question 4 and 5. The research questions and hypotheses are repeated in table 6.1.

Table 6.1: Research questions and hypothesis elaborated in section 6.1 and 6.2.

<table>
<thead>
<tr>
<th>Research question</th>
<th>Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.a</td>
<td>How did the morphological units evolve since 1970, with respect to their surface area, sediment/water volume, shape, orientation and direction of migration?</td>
</tr>
<tr>
<td></td>
<td>The sediment volume of the shoals increases while the water volume of the tidal channels decreases and the foreshore is eroding. The orientation of the morphological features is turning in a perpendicular direction to the prevailing wave direction and the channels become more elongated. The morphological units migrate in landward direction.</td>
</tr>
<tr>
<td>1.b</td>
<td>How did the entire ebb tidal delta evolve since 1970, with respect to its sediment volume, shape and orientation?</td>
</tr>
<tr>
<td></td>
<td>The sediment volume of the ebb tidal delta increased and the edge of the delta migrated in landward direction.</td>
</tr>
<tr>
<td>2.a</td>
<td>Do the morphological units act as a source (or sink) for sediment?</td>
</tr>
<tr>
<td></td>
<td>The shoals and channels act as a sink for sediment, while the foreshore us a source for sediment.</td>
</tr>
<tr>
<td>2.b</td>
<td>What is the source (or sink) of sediment for the entire ebb tidal delta?</td>
</tr>
<tr>
<td></td>
<td>The entire ebb tidal delta receives sediment from the south by alongshore sediment transport and from the south west by wave induced sediment transport. Sediment leaves the system at the north side by alongshore currents.</td>
</tr>
<tr>
<td>3.a</td>
<td>Do the morphological units show a change in sedimentation rate near 1985?</td>
</tr>
<tr>
<td></td>
<td>The occurrence of a change in sedimentation rate near 1985 is dependent on the location of the morphological unit in the ebb tidal delta. The units in the northern part show a change in sedimentation rate, while the units in the south do not.</td>
</tr>
<tr>
<td>3.b</td>
<td>Are there any specific areas where a sudden change in sedimentation rate near 1985 occurs?</td>
</tr>
<tr>
<td></td>
<td>The northern part of the area shows a change in sedimentation rate near 1985, while the southern part does not.</td>
</tr>
<tr>
<td>4</td>
<td>Is the ebb tidal delta aiming for a new morphological equilibrium state?</td>
</tr>
<tr>
<td></td>
<td>The ebb tidal delta reached a new morphological equilibrium since the construction of the dam in 1970 until the construction of the Maasvlakte 2.</td>
</tr>
<tr>
<td>5</td>
<td>Which hydrodynamic processes may have played a role in the sediment transport processes and change in morphology?</td>
</tr>
<tr>
<td></td>
<td>Sediment transport by waves is dominant over the tidal sediment transport.</td>
</tr>
</tbody>
</table>
6.1.1 Hinderplaat

The Hinderplaat (I) is the shoal situated at the edge of the foreshore (blue lines in the shoal figures 5.3, 5.4 and 5.5). Before the closure of the Haringvliet (1970), the surface area and sediment volume of the Hinderplaat already show a large increase probably induced by human intervention (section 5.2.1 and 5.2.2). Two main human-made constructions were built in this time period. The dam which closed the Haringvliet was constructed between 1957 and 1970 and the Maasvlakte 1 was constructed during the sixties of the previous century.

The influence of the dam construction was investigated using water level data near Hellevoetsluis (figure 6.1), which is a city situated inside the Haringvliet estuary. As it can be seen in figure 6.1, there is no gradual change in the water levels prior to 1970. In 1970 the water levels suddenly drop to a smaller range, which indicates a sudden failure of the tidal hydrodynamics inside the estuary. So, it cannot be concluded that the tidal hydrodynamics were influenced by the construction of the Haringvliet dam. I could not find the hydrodynamic data of the discharge in this area during the construction of the Haringvliet dam. If this data is available, it might contribute to the knowledge of hydrodynamic changes under influence of the construction of the dam. The construction of the dam caused a decrease of the cross-sectional area of the tidal basin in different stages. If the discharge did not change during the construction, the flow velocities close to the construction area must have been increased due to the decreased cross-sectional area. The change in hydrodynamics might cause erosion near the dam due to increased flow velocities and deposition at the ebb tidal area where the cross-sectional area increases and therefore the flow velocity slows down.

The impact of the Maasvlakte 1 land reclamation cannot be investigated in the scope of this research, because model studies are essential.
Between 1970 and 1980 the surface area and sediment volume of the Hinderplaat were increasing. The sediment volume was increasing with a sedimentation rate of $0.3 \cdot 10^6 \text{ m}^3 \text{ year}^{-1}$, whereas the surface area shows that the increase in surface area developed exponential in time. The exponential increase is fast prior to 1970 (rate = $0.63 \cdot 10^6 \text{ m}^2 \text{ year}^{-1}$) where after it slows down (rate = $0.15 \cdot 10^6 \text{ m}^2 \text{ year}^{-1}$). From the fact that the increase in sediment volume is fast compared to the increase of the surface area of the Hinderplaat it can be concluded that the Hinderplaat is increasing in height, which also has been shown in section 5.2.3. The increase in sediment volume and average shoal height is in agreement with hypothesis 1.a (table 6.1), because it indicates sedimentation and an increase in volume of the Hinderplaat. It also confirms the hypothesis 2.a for this period that the Hinderplaat is a sink for sediment. As it was shown in section 5.2.5, the displacement of the centroid of the Hinderplaat was in NW direction in the period prior to 1970. After 1970 until 1986 the centroid of the Hinderplaat remained quite stable in its position. However, the orientation of the Hinderplaat turned roughly from NNE-SSW into N-S in this period. Additionally the shoal became more elongated. The change in orientation, which is more or less perpendicular to the prevailing wave direction, and the fact that the Hinderplaat became...
more elongated is in agreement with hypothesis 1.a as well. Also the shape of the shoal changed dramatically in this period. In 1964 the shoal was fan-shaped broadening in seaward direction, which is a typical appearance of a tide dominated shoal. Thereafter the edges of the Hinderplaat smoothened, containing a more or less straight boundary at its seaward edge. Such a straight edge is an indication for a wave dominated environment. So, between 1964 and 1970 the shape of the Hinderplaat shows a shift between a tide and wave dominated environment. This can answer a part of research question 5 (table 6.1), for this time period (1964 – 1970) there is consensus with the hypothesis.

As it was shown in section 5.2.1 and 5.2.2, the surface area and sediment volume of the Hinderplaat decreased in the period 1986 – 1989 probably due to human interferences. This indicates a change in sedimentation rate, which answers research question 3.a and is in agreement with hypothesis 3.a, because the Hinderplaat is situated in the northern part of the area and does show a change in sedimentation rate. The main cause of this rapid decrease is the construction of the Slufter, which covers a large part of the northern Hinderplaat (figure 6.2).

Figure 6.2: The situation of the NAP -2.2 m depth contour lines in 1986 (black lines) and 1989 (red lines) with the bathymetric data of 1989. It can be seen that the Slufter partly covers the Hinderplaat.

The total surface area of 1986 which is covered by the Slufter in the bathymetry of 1989 has been calculated and contains $2.4 \times 10^6$ m$^2$ of the total surface area of the Hinderplaat in 1986. This is almost the total amount of decrease in surface area between 1986 and 1989, which can be seen in figure 6.3. The surface areas of the Hinderplaat without the influence of the construction of the Slufter are shown as a blue dotted line. The loss of $2.4 \times 10^6$ m$^2$ has been added to the surface areas of the Hinderplaat after 1986. Now it can be seen that the
decrease in surface area would be less sufficient without the construction of the Slufter. However it is necessary to make a remark about the addition of the surface area covered by the Slufter. It is assumed that the loss of surface area due to the Slufter remains constant over time. In reality this part of the Hinderplaat would have been eroded or grown in size if the Slufter was not constructed. For this reason, the addition of the lost surface area gives a non-realistic indication of the development in surface area without the influence of the Slufter. Nonetheless, it still can be recognized that the construction of the Slufter is mostly responsible for the decrease in surface area of the Hinderplaat.

Figure 6.3: Surface area of the individual shoals and the summation of all shoals (thick black line). The dotted lines indicate the situations without the construction of the Slufter. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new channel coming from the southwest, V = Supershoal.

The calculated amount of lost sediment volume due to the coverage of the Slufter is 1.5·10^6 m³, which is approximately equal to the total lost volume between 1986 and 1989. The sediment volume of the Hinderplaat without the influence of the Slufter construction is represented by the blue dotted line in figure 6.4. From this line it can be concluded that without the Slufter the decrease of sediment volume of the Hinderplaat would have been occurred after the year 1991 instead of 1986.
Concluding, both the surface area and sediment volume of the Hinderplaat show a decrease in the period 1986 – 1989, which is caused by the coverage of the Slufter. However, the decrease in surface area is more pronounced compared to the sediment volume, which indicates a vast relative increase in the average shoal height compared to the situation before. This was also observed in section 5.2.3. However, partly this relative increase can also be caused if the northern removed part of the Hinderplaat is relatively low compared to the southern part (table 6.2). The average height of the northern part in 1986 was 0.63 m and for the southern part this was 1.02 m. In 1986 the total average height of the Hinderplaat was 0.88 m and in 1989 the height was 1.3 m. So, 0.14 m (1.02 m - 0.88 m) of the total increase between 1986 and 1989 was caused due to the abortion of the relatively low northern part of the Hinderplaat. The other 0.28 m increase (instead of the total increase of 0.42 m) must have been caused by other sedimentation processes. The main sedimentation process might be that sediment which is eroded at the foreshore is deposited on top of the Hinderplaat. In figure 6.5, it can be seen that between 1986 and 1989 the Hinderplaat vastly increases in height and that it moves into landward direction. It might be possible that the
dominance of the waves relative to the tidal hydrodynamics has further increased. Waves might erode the Hinderplaat at the seaward edge where after the sediment will be deposited on top of the Hinderplaat and at the landward side of the Hinderplaat.

After 1991 the surface area seems to stabilize while the sediment volume is decreasing, this results in a strong decrease of the average shoal height (figure 6.6). As it can be seen in figure 6.5, the maximum height of the shoal does not increase that much compared to the situations before. However, the cross-sectional area of the Hinderplaat decreases a lot and it becomes a high and narrow shoal. This contributes to the decreases in average shoal height. The Hinderplaat most likely has been eroded by waves at the seaward side.

The displacement of the centroid of the Hinderplaat is influenced by the construction of the Slufter as well. It suddenly shifts towards the south in the period 1986 – 1989, caused by the reduction of the surface area at the northern side of the Hinderplaat.
Figure 6.6: Average height of the individual shoals and the summation of all shoals (thick black line). The dotted lines indicate the situations without the construction of the Slufter. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new channel coming from the southwest, V = Supershoal.

Table 6.2: Average shoal height between 1986 and 1989 and the influence of the Slufter to the increase and decrease in height.

<table>
<thead>
<tr>
<th></th>
<th>1986</th>
<th>1989</th>
<th>Increase / decrease</th>
<th>Slufter influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average height northern part</td>
<td>0.63 m</td>
<td>-</td>
<td>-0.63 m</td>
<td>-0.63 m</td>
</tr>
<tr>
<td>Average height southern part</td>
<td>1.02 m</td>
<td>1.3 m</td>
<td>0.28 m</td>
<td>0.14 m</td>
</tr>
<tr>
<td>Average height entire shoal</td>
<td>0.88 m</td>
<td>1.3 m</td>
<td>0.42 m</td>
<td></td>
</tr>
</tbody>
</table>

### 6.1.2 Northern and southern Garnalenplaat

The northern (II) and southern (III) Garnalenplaat are the shoals closest to the Haringvliet dam (red and green lines, respectively in the shoal figures 5.3, 5.4 and 5.5). As it was shown, the northern Garnalenplaat was already present between 1964 and 1989 above NAP -2.2 m, while the southern Garnalenplaat was not. Both the surface area and sediment volume of the northern Garnalenplaat seem not to change much in this period. However, when the average shoal height is plotted (figure 5.5), it can be concluded that the northern Garnalenplaat increases in height until 1970 where after it lowers until 1980. The lowering of the northern Garnalenplaat caused by a decrease in sediment volume is in contradiction with...
hypothesis 1.a and 2.a, because it indicates erosion instead of sedimentation and that it acts as a source for sediment instead of a sediment sink. However, the lowering of the Garnalenplaat was also mentioned by Postma et al. (1990). They suggested that a decrease in sediment supply is the cause of the lowering of the landward shoals. This also might indicate the source of sediment for the northern Garnalenplaat. So the decrease of the ebb current (decrease of the Haringvliet outflow) decreases the sediment supply out of the Haringvliet. If the sediment supply from other sources is not sufficient for the growth of the northern Garnalenplaat, erosion by waves becomes dominant at this shoal resulting in a decreasing average shoal height and sediment volume.

In section 5.2.1 and 5.2.2 it was mentioned that the rate of surface area increase and sedimentation (sediment volume and average shoal height) of the northern Garnalenplaat increased after 1986 (the average shoal height already increased from 1980). Additionally, the southern Garnalenplaat suddenly rose above the NAP -2.2 m depth contour line and thus the sedimentation rate was increasing in this area as well continuing until 2003. These alterations are in consensus with the hypotheses 1.a and 2.a.

After 1986 the northern and southern Garnalenplaat increase in volume and act as a sink for sediment. These sudden changes are remarkable, especially because they occurred in the period 1986 - 1989. This observation is not in agreement with hypothesis 3.a. There is a change in sedimentation rate near 1985, but these shoals are situated in the southern part of the delta, whereas the hypothesis states that only the morphological units in the northern part show a change in sedimentation rate.

A specific reason for the alteration of the northern Garnalenplaat from a source to a sink for sediment and the fact that the southern Garnalenplaat is rising above the NAP -2.2 m after 1989 can be the construction of the Slufter. It could be that the construction altered the hydrodynamics in the area. Because the Slufter extends the coastline in the southern direction, the tidal current has to flow to the sea more southward compared to the situation without the Slufter (figure 6.7, red arrow). This more southern flow might enlarge the shadow sedimentation zone in front of the dam causing an increase in sedimentation. In this larger shadow zone, the northern and southern Garnalenplaat are situated. In the scope of this research it cannot be proved that such a tidal current alteration is a reasonable solution, but for further research model studies could be useful to define the differences in tidal hydrodynamics and sedimentation caused by the Slufter construction. In a model study two scenario’s, one with and one without the Slufter, could be investigated to define the influences of such a large human interference on tidal hydrodynamics and sediment transport.

The migration of the northern Garnalenplaat is towards the north, whereas the southern Garnalenplaat is quite fixed in one location. The reason that the southern Garnalenplaat
stays fixed in one location is probably the fact that this shoal does function as a kind of levee of the Slijkgt (L.Hoek, Rijkswaterstaat, personal communication, 6 November 2013 and A. van der Spek, Deltares, personal communication, 25 November 2013). Under natural conditions, the southern Garnalenplaat is migrating in seaward direction, but the dredging activities of the Slijkgt are obstructing this. Every time the western edge of the southern Garnalenplaat extends in seaward direction and fills part of the Slijkgt, the material will be dredged. In this way the southern Garnalenplaat is prevented from growing westward. This is both in contradiction with the hypothesis that the morphological units would migrate in landward direction. In fact, the shoals finally migrate to the central part of the area, where all shoals will connect and form the Supershoal.

Figure 6.7: Possible tidal current alteration due to the Slufter construction. In black the contour lines and tidal current (arrow) before the presence of the Slufter and in red the situation afterwards.

6.1.3 Supershoal
The Supershoal (V) is the large shallow area which develops in the central part of the Haringvliet delta area (grey line in the shoal figures 5.3, 5.4 and 5.5). The Supershoal starts to develop after 1998 with the growth of the new shoal coming from the southwest. In 2001 the new shoal has been merged to the Hinderplaat and thereafter the northern and southern Garnalenplaat will join the Supershoal in 2003 and 2009, respectively as well. As it was said in section 5.2.1 and 5.2.2, the main cause of the Supershoal growth in surface area and sediment volume was caused by the junction of the northern and southern Garnalenplaat. The situation where the northern and southern Garnalenplaat would not merge with the Supershoal has been illustrated in figure 6.8, 6.9 and 6.10 by the grey dotted line. Observing
the surface area and sediment volume in this modified case, shows that the rate of increase in surface area and sediment volume would be much slower until 2009. However, in the period 2009 – 2012 the surface area and sediment volume of the Supershoal (V) still shows a strong increase in the modified situation and it verifies hypothesis 1.a and 2.a because it acts as a sink for sediment. Because there is no reasonable explanation for such a large increase on such a small time scale (approx. $3 \times 10^6$ m$^3$ sediment in 3 years), it is probably caused by human interventions. The biggest human interference in this period is the construction of the Maasvlakte-2 (a new land reclamation situated in the northwest of this area, constructed between 2008 and 2013). During the construction suspended sediment concentrations might have increased in the water column due to the replenishments. The suspended sediment might be transported towards the south by the ebb current, where it will be deposited. The report of the effects of the construction of the Maasvlakte 2 on the environment shows that the annual averaged silt concentrations in the foreshore can increase with a maximum of 6 mg/liter (Berkenbosch, 2007). The suspended silt particles can be transported with the tidal currents in both the southern and northern direction. And thus it can also be transported towards the former ebb tidal delta of the Harlingvliet. Another possible cause of the strong increase could be that the area around the NAP -2.2 m contour line suddenly rose above the depth contour line resulting in an increase in surface area and sediment volume. To prove if this is what happened, the vertical distribution of the surface area and sediment volume in the ebb tidal delta needs to be calculated. The sediment volume of the shoals calculated to different reference depths is shown in figure 5.6. This figure shows that all the sediment volumes calculated at different reference depths show a strong increase in sediment volume in the period 2009 – 2012. It can be recognized that the increase in sediment volume of the shallower parts is less sufficient compared to the deeper parts. It has to be kept in mind that the increase is only based on the data of two time steps, which causes uncertainties in the accuracy of the strongly increasing trend. However, because the sediment volumes of all reference depths shows a large increase between 2009 and 2012 compared to the period before it can be carefully concluded that the large increase is not caused by a sudden rise of deeper parts containing a large surface area.
Figure 6.8: Surface area of the individual shoals and the summation of all shoals (thick black line). The grey dotted line indicates the development of the Supershoal if the northern (II) and southern (III) Garnalenplaat did not merge with the Supershoal. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new channel coming from the southwest, V = Supershoal.
Figure 6.9: Sediment volume of the individual shoals and the summation of all shoals (thick black line). The grey dotted line indicates the development of the Supershoal if the northern (II) and southern (III) Garnalenplaat did not merge with the Supershoal. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new channel coming from the southwest, V = Supershoal.
Figure 6.10: Average height of the individual shoals and the summation of all shoals (thick black line). The grey dotted line indicates the development of the Supershoal if the northern (II) and southern (III) Garnalenplaat did not merge with the Supershoal. I = Hinderplaat, II = northern Garnalenplaat, III = southern Garnalenplaat, IV = new channel coming from the southwest, V = Supershoal.

6.2 Morphological development of the channels

In this section the morphological development of the channels will be discussed based on the results described in section 5.3 to test the hypotheses 1.a, 2.a and 3.a (table 6.1).

6.2.1 Rak van Scheelhoek

The Rak van Scheelhoek (I) is the large channel situated in front of the southern coast of Voorne (blue line in the channel figures 5.13, 5.14 and 5.15). After 1970, the surface area and water volume keep on decreasing until the channel disappeared after 1991. This confirms the hypotheses 1.a and 2.a (table 6.1). The channel is infilling with sediment and thus decreases in volume indicating that it acts as a sink for sediment. However, between 1972 and 1976 the decrease in surface area and sediment volume is partly caused by the abortion of the northern part of the channel, the Gat van de Hawk (IV). When the average depth of the channel is observed, it shows a decreasing trend as well. This indicates that the
channel is filling with sediment. This can be explained by the decrease of the tidal prism. The current velocities through the ebb channels decreased, causing sedimentation and consequently the silting up of the Rak van Scheelhoek. The Rak van Scheelhoek does not show a clearly recognizable change in sedimentation rate near 1985, which is in contradiction with hypothesis 3.a (table 6.1). However, the Rak van Scheelhoek silted up very quickly after the closure of the Haringvliet dam and disappeared almost near 1986 already. Thus, the development of the channel was not highly influenced by the construction of the Slufter.

6.2.2 Bokkegat
The Bokkegat (III) is a side-branch of the Rak van Scheelhoek in the central part of the former Haringvliet ebb tidal delta (green line in the channel figures 5.13, 5.14 and 5.15). The Bokkegat shows a strong decreasing trend in surface area, sediment volume and average water depth between 1970 and 1980. This is in agreement with the hypotheses 1.a and 2.a. The volume of the channel decreases and it acts as a sink for sediment. Between 1980 and 1986 the decrease in the dimensions of the Bokkegat are less significant and the surface area, sediment volume and average water depth are quite stable. This might indicate that the channel is going towards a new equilibrium state (research question 4). When a system is turning into a new equilibrium, the morphological changes are fast in the beginning (1970 – 1980) where after the rate of morphological change ceases (after 1980). Another observation after 1980 was that the channel starts to migrate in southern direction (figure 5.19). The reason for this might have to deal with the alteration of the Hinderplaat. After 1970 the orientation of the Hinderplaat is turning perpendicular to the prevailing wave direction and it is also extending in southward direction. The Bokkegat is situated at the southern edge of the Hinderplaat and thus migrates in southern direction. Its orientation turns slightly in the direction which is similar to the orientation of the Hinderplaat and is in agreement with hypothesis 1.a. Where between 1980 and 1986 the Bokkegat seems to stabilize and is going to a new equilibrium, it becomes unstable after 1986. The sediment volume of the channel increases while the surface area does not change very much, resulting in an increasing average water depth. This might indicate erosion of the Bokkegat. The sediment volume and therefore the average channel depth begin to decrease again after 1996. Because this phenomenon suddenly occurs after 1986, the logical way of thinking is that the cause has something to do with the construction of the Slufter. One explanation might be that the Slufter decreases the area over where the tide can flow. Where, before the Slufter existed, the flood current entered the area in the southwest and left in the north, it now has to turn off at a more southward location. If this happens, the flood comes in through the Bokkegat in the south and leaves the area through the Hindergat in the
north (figure 6.7, red arrow). Then the same amount of water has to enter and leave the area, but in a smaller amount of time. This results in increasing current velocities and consequent erosion. When the hydrodynamics are adapted to the new morphology the tidal prism decreases, causing current velocities to decrease. This in turn increases the amount of sedimentation in the Bokkegat causing a decrease of the average water depth until it disappeared after 2001.

### 6.2.3 Gat van de Hawk / Hindergat

The Gat van de Hawk (IV) is a side-branch of the Rak van Scheelhoek towards the north, after the construction of the Slufter this channel was excavated south of the Slufter and is from then called Hindergat (IV) (magenta line in the channel figures 5.13, 5.14 and 5.15). From 1976, when the Gat van de Hawk is no longer attached to the Rak van Scheelhoek at the NAP -5 m depth, until 1986 the Gat van the Hawk is a more or less stable channel. Between 1976 and 1980 the surface area decreases and at the same time the water volume does not change much. This results in an increasing average water depth of the channel, as it can be seen in figure 5.15. Because the Gat van de Hawk is situated in the northern seaward side of the area, it acts as an in- and outlet for the tidal currents. Therefore it probably has to increase in size to accomplish its task. If the channel is too small for the tidal discharge, the tidal current velocities increase causing erosion and therefore the average water depth increases.

After 1980 the rate of increase in the average water depth is slowing down and it seems that it is going to a new equilibrium state. This also happened to the Bokkegat, it first shows a fast change, where after the rate of change ceases. Suddenly, after 1986, the water volume of the Gat van de Hawk increases while the surface area stays more or less stable. This results in a sudden deepening of the channel. Additionally, the centroid of the channel shifts towards the south over a long distance. This comprehensive change is mainly caused by the construction of the Slufter and the coherent excavation of the Hindergat. The fact that the Hindergat has been excavated by humans can be recognized in the figure of the average water depth (figure 5.15). In the period 1986-1989 there is a strong deepening of the channel. It is most likely that such a large change does not occur naturally because natural changes are more gradual and thus is probably caused by humans. Actually the Hindergat was excavated at the southern edge of the Slufter (A. van der Spek, Deltares, personal communication, 25 November 2013).

After 1990 there is a sudden drop of the average water depth as well. Probably the Hindergat was excavated too deep and is adapting to the new situation. This occurs by the infilling of the channel with sediment, because the surface area remains stable and the water volume decreases. The average water depth does decrease after 1990, however it does not
decrease until its former depth before 1986. This might point at an alteration of the tidal hydrodynamics. The construction of the Slufter over the former opening in the north probably caused a stronger curvature of the tidal currents, as it was earlier described in section 6.1.2 and figure 6.7. If the tidal prism remains equal, the current velocities in the Hindergat have to increase to discharge water to the sea (during flood) and let the water flow in (during ebb). The increasing current velocities cause erosion of the Hindergat, resulting in a larger water volume and average water depth of the channel (compared to the situation before 1986).

6.2.4 Slijkgat
The Slijkgat (V) is a channel in the southern part of the area, which gives access to the North Sea for the Stellendam harbour (grey line in the channel figures 5.13, 5.14 and 5.15). Just like the Rak van Scheelhoek, the Slijkgat also shows a decrease of the surface area, water volume and average water depth until 1990. The decrease in water depth is mainly caused by the decrease of water volume in the Slijkgat. This indicates the infill, and thus sedimentation, of the channel. This is in consensus with hypothesis 1.a and 2.a, because the Slijkgat is now a sink for sediment. Until 1980 the decrease in average water depth is faster compared to the period 1980 – 1986, where it more or less stabilizes. The fast change in the first 10 years after the dam construction followed by more or less stabilization might indicate that the Slijkgat was reaching a new equilibrium suitable for the decreased tidal prism. This also happened with the Bokkegat and Gat van de Hawk.

Between 1986 and 1989 the surface area and sediment volume of the Slijkgat both decrease. The decrease in sediment volume is larger compared to the surface area, resulting in a strong decreasing average water depth. Because this happens in the same period of the Slufter construction, it might be that this has influenced the Slijkgat as well. A stronger curvature of the tidal current due to the southward displacement of the Hindergat (gat van de Hawk), which was described in section 6.1.2 and figure 6.7, might increase the surface of the shadow area close to the dam, and thus sedimentation of the eastern part of the Slijkgat (closest to the dam).

After 1989, the average water depth is slightly increasing due to the increase in water volume. Additionally, the increase is the largest between 1996 and 2001. This is probably caused due to the change in dredging treatment in this channel since the year 2000. Prior to 2000 the dredging of the Slijkgat was managed such that a shipping lane of 4 m deep with a width of 200 m was maintained (blue area in figure 6.11). This dredging depth was shallower than the reference depth whereto the Slijkgat was referenced (NAP -4.4 m). Therefore, the dredging activities did not influence the surface area and sediment volumes below the reference depth directly. The dredged material was mainly used for sand mining for commercial purposes. After 2000, there were some changes in the coastal policy. One of the
changes was a change in the dredging depth. In the period 2000 – 2005 the dredging of a 4 m deep and 200 m wide navigation channel remained were in the centred 100 m the dredging depth was increased to a water depth of NAP -5 m (red area in figure 6.11). This causes a larger increase in the water volume rather than the surface area, resulting in an increased average water depth. After 2005 the dredging policy of the Slijkgat changed due to the introduction of the Natura 2000 law and the fact that it was no longer allowed to subtract sediment from the Dutch coastal foundation for safety reasons (in Dutch: kustfundament). Dredging of the Slijkgat was still required, but the dredged material was no longer subtracted from the coastal system and is now dumped at an appointed location seaward of the NAP -10 m contour line (figure 6.12). Additionally, after 2005 until today the dredging depth of the centred 100 m part was increased down to NAP -5.5 m (green area in figure 6.11). This latter change in the dredging activities cannot be recognized in the results of the surface area (figure 5.13), water volume (figure 5.14) and average water depth (figure 5.15). Because the dredging was extended to a larger volume it would be expected that the water volume and thus the average water depth increase. This is not the case; in fact these morphological features show a slightly decreasing trend. Due to the fact that the water volume and surface area both are slightly decreasing instead of increasing, it means that in the areas which are broader than 200 m below the reference depth NAP -5 m sedimentation might have taken place at the edges of the channel (figure 6.11, white edge areas below the reference depth). Furthermore, the fact that the morphological features of the Slijkgat become quite stable after 2005 probably is caused by the fact that the frequent dredging of the Slijkgat maintains the morphology of the channel.

Figure 6.11: Dredging policy of the Slijkgat. Information source: L. Hoek, Rijkswaterstaat, personal oral communication, 6 November 2013.
6.2.5 New breakthrough channel

The new breakthrough channel (VI) is a channel which divides the Supershoal into two segments (cyan line in the channel figures 5.13, 5.14 and 5.15). In 2001 the contours at NAP -5 m of the channel are present. The average depth of the channel first shows a large increase until 2003. Thereafter the rate of increase in water volume decreases and seems to stabilize. It is remarkable that just when the Supershoal starts to develop the new channel develops as well. Additionally the water volume of the Hindergat is decreasing. This might indicate an alteration of the tidal hydrodynamics. Because a new shoal is attaching to the southern part of the Hinderplaat, the in- and outflow channel in the south (Bokkegat) becomes suppressed. This can hinder the tide from flowing from south to north and back. The new channel is W-E oriented, indicating in- and outflow from west to east. The following question is: Is the tidal system shifting again? This cannot be determined at this moment, because more data is necessary to substantiate this pronouncement.
6.3 Sediment volume changes in the entire ebb tidal delta

In this section it will be elaborated how the sediment volume of the entire ebb tidal delta changes after the closure of the Haringvliet basin based on the results described in section 5.4 to answer the research questions and test the hypotheses of 1.b, 2.b, 3.b and 4 can be tested. These research questions and hypotheses are shown in table 6.1.

As it was shown in section 5.4, the sediment volume increases with a large amount in the first 10 years after the construction of the Haringvliet dam (1970 – 1980, figure 5.23). After 1980 the sedimentation rate strongly decreases, but the sediment volume is still increasing. This confirms part of the hypothesis 1.b (table 6.1), where it was stated that the sediment volume of the ebb tidal delta increased after 1970. The second statement of this hypothesis, that the edge of the delta migrated in landward direction, can be confirmed due to the illustration of figure 6.5. In this figure it can be seen that the edge of the entire ebb tidal delta systematically migrates in landward direction.

The appearance of large morphological changes just after a human interference followed by an extinguishing sedimentation rate (changing after 1980) might indicate that the morphodynamic system of the former Haringvliet ebb delta is going to a new morphodynamic equilibrium state. However, the equilibrium might be disturbed in the period 1989 – 1992, because the stable sediment volume of the entire ebb tidal delta shifts to a larger sediment volume in a relatively short time period. Despite this observation, it must be taken carefully, because it is only based on the data of two time steps. But, it might be a reaction of the construction of the Slufter. In section 6.1.2 it was suggested that the appearance of the Slufter altered the curvature of the tidal currents in the former Haringvliet ebb tidal delta area (figure 6.7). This can increase the surface area of the “shadow zone” near the Haringvliet dam. In this “shadow zone” flow velocities are low, resulting in sedimentation in this area. This causes a shift of the entire ebb tidal delta towards a higher sediment volume, where after it stabilizes, indicating that the system has been adapted to the new conditions with the Slufter.

Because the adaptation to the Slufter occurs within less than 5 years the effect of the Slufter on the hydro- and morphodynamics is less severe compared to the adaptation to the Haringvliet dam (within more than 10 years). After 2009 the stabilizing tendency of the sediment volume has disappeared and the sediment volume is strongly increasing towards 2012. The drop between 2006 and 2009 is probably caused by a small area containing “no data” and thus is not representative for the actual sediment volume in 2009. In reality this number would be slightly higher and the sedimentation rate in the period 2009 – 2012 would be smaller. The strong increase in sediment volume was also recognized in the calculations.
of the Supershoal (section 6.1.3, figure 6.8). Two reasons for this large increase were given. One reason was that the construction of the Maasvlakte 2 increased the amount of suspended sediments in the water column, resulting in an increased sedimentation volume in the area. Whether such an effect is possible or not cannot be investigated in the scope of this research and therefore model studies are needed to solve this hypothesis. The second reason mentioned was that the area already was filled with sediment just below the reference depth of NAP -2.2 m and suddenly rose above the reference depth. This would have been a small increase in height but over a large surface area, resulting in a vast increase in sediment volume.

From the above observations it can be concluded that the sediment volume of the entire ebb tidal delta was going towards a new equilibrium state, but this was probably disturbed by the construction of the Slufter and the Maasvlakte 2. So the hypothesis 4 can partly be confirmed. The entire ebb tidal delta was aiming for a new morphological equilibrium state since 1970 until the construction of the Maasvlakte 2. However, the Slufter probably caused a small interruption.

When comparing the increase in sediment volume relative to the sediment volume in 1970 of the entire delta, the channels and the shoals, it can be observed that the development of the shoals takes a different course compared to the development of the channels and the entire delta (figure 5.24). The development of the entire delta and the channels shows a similar pattern with strong increasing sediment volumes just after the construction of the Haringvliet dam (1970) until 1980, where after the sedimentation rate decreases indicating that the delta and the channels are going to a new equilibrium state. The shoals also show a faster sedimentation rate between 1970 and 1980, where after it stabilizes. However after 1998, the relative sediment volume increase to 1970 is larger from 2003 and the sedimentation rate increases after 2006. So, the shoals above NAP -2.2 m were also going towards a new equilibrium state, which has been disturbed between 1998 and 2003. It is not that remarkable that the distribution of the channels first decreased, where after the shoals became more and more important. The areas below NAP -5 m are the deeper parts of the former ebb tidal delta, which functioned as the ebb tidal channels. Because the ebb current decreased, the former ebb tidal channels silted up. When these channels were filled with sediment, the parts higher than NAP -5 m and lower than NAP -2.2 m of the former ebb tidal delta could be filled up with sediment. This happened probably in the period where both the distribution of the shoal and channel parts does not show significant changes. After 2003 the distribution of the area above NAP -2.2 m increased and thus the infilling of the channels became less important.

When the 4 main areas area observed (central part, Kwade Hoek, foreshore and the Westplaat) (figure 5.26), it can be concluded that the foreshore is vastly eroding, because it
is decreasing in sediment volume. This indicates that the foreshore is a source for sediment. At the same time, the central part with the channels and shoals receives a lot of sediment during the same time period and thus is a sink for sediment. Because the sediment volume of the Westplaat is not significantly changing, it can be assumed that the Westplaat is not a source of sediment for the central part of the ebb tidal delta. The sediment volume of the Kwade Hoek is increasing (figure 5.26), acting as a sink for sediment. Therefore, the Kwade Hoek probably is not a source of sediment for the central part of the ebb tidal delta. Additionally, the Kwade Hoek does migrate in north-western direction where it meets the Slijkgat. If it fills up the Slijkgat, the sediment is dredged and is subtracted from the system (1970 – 2005) or deposited seaward of the area below the NAP -10 m (figure 6.12). In figure 6.5 it can be seen that the NAP -10 m depth contour line is migrating slower in landward direction compared to shallower depths, and thus the landward transportation of the dredged material of the dump location is less significant than at shallower depths. It is therefore assumed that the Kwade Hoek is less important for the sediment supply in the central part compared to the sediment supply of the foreshore.

The eroded sediment of the foreshore can be transported towards the central part of the area by waves, but is it is also partly transported in alongshore direction. If it is now assumed that all the sediment eroded at the foreshore is deposited at the central part, it can be concluded that the sediment supply of the foreshore is not sufficient to be fully responsible for the sediment volume increase of the entire ebb tidal delta (figure 5.27, green line) and thus other sources might be responsible for this (figure 5.27, red line). Other sediment sources might be alongshore sediment transport, sediment transport out of the Haringvliet basin during high river discharges and as it was noted earlier the Kwade Hoek might have a contribution. The hypothesis of 2.b (table 6.1) can partly be confirmed by the above arguments. The ebb tidal delta receives sediment from the foreshore induced by the motion of waves, but there are also other sources that supply sediment for the former Haringvliet ebb tidal delta.

6.4 Movement of the centroids
For the definition of the displacement of the morphological units, it is not possible to use solely the centroid of the morphological unit. The centroid can be displaced due to several reasons. One reason is non-uniform growth or decrease of the surface area of the polygon or deformation of the shape of the polygon. The other reason is the displacement of the morphological unit in its totality. Additionally, if the growth or decrease of the polygon is uniform around its edges, the centroid of the morphological unit is fixed at its location.
Therefore the displacement of the centroids needs to be combined with the polygons around the morphological units to make an interpretation of the migration of the units.
7. Conclusions

This research was carried out to investigate the morphological development of the individual morphological units which are part of the former Haringvliet ebb tidal delta under influence of the construction of the Haringvliet dam. In this chapter the conclusions of the discussed results will be summarized. First the results of the sub-questions of the research will be given. Thereafter the results of the sub-questions are used to answer the main research question.

1.a How did the morphological units evolve since 1970, with respect to their surface area, sediment/water volume, shape, orientation and direction of migration?

The morphological development of the shoals cannot be generalized because the Hinderplaat behaves different from the northern and southern Garnalenplaat and the Supershoal. In the period 1970 – 1980 the Hinderplaat increases in size, while the northern Garnalenplaat is decreasing in size. The southern Garnalenplaat and the Supershoal are not yet present in this time period. The sediment volume of the Hinderplaat increases, causing an increase of the average shoal height. The behaviour of the northern Garnalenplaat is opposing the Hinderplaat. The sediment volume and average shoal height of the northern Garnalenplaat are decreasing. After 1980 the sediment volume of the Hinderplaat decreases, whereas the sediment volume of the northern Garnalenplaat is increasing. The surface area, sediment volume and average shoals height of the Supershoal, which develops in 2001, are increasing. The location of the Hinderplaat is quite stable except for the period 1986 – 1989, where the northern part of the Hinderplaat is abandoned because the Slufter has been constructed on top of the Hinderplaat. However, the Hinderplaat does turn in an orientation perpendicular to the prevailing wave direction. The northern Garnalenplaat is extending in northern direction, while the southern Garnalenplaat stays in the southern part of the area. Finally all shoals will be connected to each other in the central part of the former ebb tidal delta to form the Supershoal.

The Rak van Scheelhoek is filling with sediment until it disappears in 1992. The rate of infilling is faster until 1979, where after it slows down. The same way of infilling is occurring in the Bokkegat and the Slijkgat. The development of the Bokkegat, Gat van de Hawk / Hindergat and the Slijkgat has been disturbed in the period 1986 – 1989, whereby the infilling of the Slijkgat speeds up and the water volume of the Bokkegat and Gat van de Hawk / Hindergat is increasing. After 2000 the development of the Slijkgat becomes more or less artificial, because due to changes in the dredging policy the morphological features of the channel become fixed. The position of the Slijkgat does not change much and the Rak
van Scheelhoek is retreating towards the dam. The Gat van de Hawk / Hindergat only shifts towards the south in the period 1986 – 1989 due to the construction of the Slufter. The Bokkegat stays south of the Hinderplaat and turns in a direction more perpendicular to the prevailing wave direction.

Taken the above results in mind, the hypothesis of this research question can be tested:

“The sediment volume of the shoals increases while the water volume of the tidal channels decreases and the foreshore is eroding. The orientation of the morphological features is turning in a perpendicular direction to the prevailing wave direction and the channels become more elongated. The morphological units migrate in landward direction.”

The hypothesis partly can be confirmed. Not on / in all shoals and channels sedimentation occurs, some do erode. This is also dependent on the time period. The orientation of the seaward situated morphological units (Hinderplaat and Bokkegat) turns in a direction perpendicular to the prevailing wave direction, where the landward units (Rak van Scheelhoek and the northern and southern Garnalenplaat) do not.

1.b How did the entire ebb tidal delta evolve since 1970, with respect to its sediment volume, shape and orientation?

In the period 1970-1980 the increase in sediment volume of the entire delta is fast. The sedimentation rate decreases after 1980 until 1989. Then the sediment volume shifts to a larger volume probably caused by the presence of the Slufter, where after it stays more or less stable until it shows a strong increase after 2009. The latter increase is probably caused by the construction of the Maasvlakte 2, but this needs to be further investigated. It was also observed that the edge of the ebb tidal delta migrated in landward direction.

Considering the results of the sediment volume of the entire ebb tidal delta, there is consensus with the hypothesis of this research question:

“The sediment volume of the ebb tidal delta increased and the edge of the delta migrated in landward direction.”

2.a Do the morphological units act as a source or sink for sediment?

When all shoals are taken together, they act as a sink for sediment. However, the individual shoals mutually differ. In the period 1970 – 1980 the Hinderplaat acts as a sink for sediment, while the northern Garnalenplaat is a source for sediment. After 1980 this will be reversed, the Hinderplaat becomes a source for sediment and the northern Garnalenplaat a sink for sediment. In 1989 the southern Garnalenplaat rises above the NAP -2.2 m and is also a sink for sediment, just like the Supershoal which starts to develop in 2001.
The Rak van Scheelhoek, Bokkegat and Slijkgat act as a sink for sediment. However, the Gat van de Hawk / Hindergat and the new breakthrough channel which divides the Supershoal act as a source for sediment. Also the Slijkgat becomes a source for sediment after 2000, but this has no natural cause because this channel has a high dredging frequency.

Reverting to the hypothesis:

“The shoals and channels act as a sink for sediment, while the foreshore is a source for sediment.”

it can be partly confirmed and it is partly rejected. The seaward shoal (Hinderplaat) first is a sink for sediment until 1980, thereafter it becomes a source for sediment. The landward shoals (northern and southern Garnalenplaat) are showing the opposite. The channels are mainly a sink for sediment, but after 1986 the Bokkegat and Hindergat temporarily act as sediment sources.

2.b What is the source or sink of sediment for the entire ebb tidal delta?

The entire ebb tidal delta itself acts as a sink for sediment, because its sediment volume keeps on increasing. When the entire ebb tidal delta is subdivided into 4 main areas, it can be concluded that the central part (which contains the former tidal channels and shoals) and the Kwade Hoek are acting as a sink for sediment. The foreshore acts as a source for sediment. It seems that the foreshore is one of the main sources of sediment for the central part of the ebb tidal delta. However, the sediment supply to the central part is also caused by other sources.

Therefore the hypothesis of this research question can partly be confirmed:

“The entire ebb tidal delta receives sediment from the south by alongshore sediment transport and from the south west by wave induced sediment transport. Sediment leaves the system at the north side by alongshore currents.”

3.a Do the morphological units show a change in sedimentation rate near 1985?

All shoals do show a change in sedimentation rate near 1985. The change in sedimentation rate occurs in the period 1986 – 1989. In this time period the Slufter (a large depot for dredged material) was constructed and is the most possible cause of the changes in sedimentation rate. The change in sedimentation rate of the Hinderplaat was altered due to the fact that the Slufter was partly built on top of the Hinderplaat. Sedimentation in and on the morphological units at the landward side of the area showed a change in sedimentation rate due to the alteration of the course of the tidal currents. This created a larger
sedimentation zone near the Haringvliet dam.
The sedimentation rate of the Rak van Scheelhoek does not show significant changes near 1985. However, the Bokkegat and Hindergat do show an increase in the erosion in the period 1986-1989. Additionally, sedimentation increase in the Slijkgat in this time period.
Considering the hypothesis of this sub-question:

“The occurrence of a change in sedimentation rate near 1985 is dependent on the location of the morphological unit in the ebb tidal delta. The units in the northern part show a change in sedimentation rate, while the units in the south do not.”

it can be concluded that the hypothesis cannot be confirmed. The change in sedimentation rate is not dependent on the location of the morphological unit in the ebb tidal delta, because all shoals and channels (except for the Rak van Scheelhoek) show a change in sedimentation rate in the period 1986 – 1989.

3.b Are there any specific areas where a sudden change in sedimentation rate near 1985 occurs?
The entire ebb tidal delta shows a shift in the sedimentation course after 1989. Probably this was also caused by the construction of the Slufter, causing a change in the course of the tidal flow. In the calculations the northern part containing the Slufter area was not included, so the southern part also shows a change in the sedimentation rate. Additionally, the answer of sub-question 3.a already stated that several morphological units in other parts than the northern part of the ebb tidal delta also did show a change in sedimentation rate near 1985. Therefore the hypothesis:

“The northern part of the area shows a change in sedimentation rate near 1985, while the southern part does not.”

cannot be accepted.

4. Is the ebb tidal delta aiming for a new morphological equilibrium state?
The development of the sediment volume of the entire ebb tidal delta does show an exponential course which is characteristic for a new equilibrium. The adaptation just after the construction of the Haringvliet dam occurs fast in the first 10 years (1970 – 1980), where after the sedimentation rate decreases. The exponentially decreasing sedimentation rate indicates that the delta is going towards a new equilibrium state. This pattern was also recognized in the sedimentation rate of several morphological units. For the entire ebb tidal delta the tendency
for a new equilibrium was temporarily interrupted in 1989, where after it was again aiming for a new equilibrium state. However between 2009 and 2012 this course was disturbed (probably by the construction of the Maasvlakte 2) showing a fast increase of the sediment volume.

Because of these results the hypothesis:

“The ebb tidal delta reached a new morphological equilibrium since the construction of the dam in 1970 until the construction of the Maasvlakte 2.”

can be accepted for the larger part, because the entire ebb tidal delta had the tendency to reach a new equilibrium state before the construction of the Maasvlakte 2, which started in 2008. However this course towards an equilibrium state was temporarily disturbed in 1989.

5. Which hydrodynamic processes may have played a role in the sediment transport processes and change in morphology?

The shape of the Hinderplaat changes in 1970 from a tide dominated shoal into a wave dominated shoal. This indicates that the hydrodynamics changed and that the wave motions became dominant over the tidal currents. This is in consensus with the hypothesis of this research question:

“Sediment transport by waves is dominant over the tidal sediment transport.”

Additionally, the northern Garnalenplaat decreased in sediment volume and height in the period 1970 -1980. This is probably caused due to the fact that erosion by waves became dominant over the sediment supply of the ebb current.

Considering the results of the sub-questions, the main research question “How did the morphology of the Haringvliet ebb tidal area evolve since the delivery of the Haringvliet dam in 1970?” can be answered as follows:

Before the closure of the Haringvliet dam (1970), the Hinderplaat was already a sink for sediment. The reason for this cannot be stated, because a lot of human activities might have influenced the morphological development of the area. It needs to be investigated what the influences of the construction of the Maasvlakte 1 and the construction of the Haringvliet dam itself were on the morphological development of the Haringvliet ebb delta.

In the period 1970 – 1980, large adaptations occur due to the construction of the Haringvliet dam. The Hinderplaat, Rak van Scheelhoek, Bokkegat and Slijkgat are gaining sediment and
thus act as a sink for sediment. The northern Garnalenplaat is decreasing in height and is therefore a source for sediment. The shape of the Hinderplaat turns from a tide dominated appearance into a wave dominated shape. The orientation also turns into a direction perpendicular to the prevailing incoming wave direction. Because the Bokkegat is situated at the southern edge of the Hinderplaat, this channel turns into a similar orientation. The shape of the other morphological units does not change much, except for the fact that the surface area of the channels decreases and of the shoals increases.

In the period 1980 – 1986 the Rak van Scheelhoek, Bokkegat, Slijkgat and Gat van de Hawk seem to approach an equilibrium state. The Hinderplaat changes from a sink for sediment into a source for sediment, due to increased erosion by waves. However, these trends will be interrupted in the period 1986 – 1989 by the construction of the Slufter in the northern part of the area. The Slufter covers the northern part of the Hinderplaat, causing a decrease in sediment volume. It seems that the northern and southern Garnalenplaat, Bokkegat, Slijkgat and Hindergat are also adapting to this change. The sediment volume of the northern and southern Garnalenplaat increases (sink for sediment) and the average water depth of the Bokkegat and Hindergat is increasing (source for sediment). A possible explanation is that the tidal hydrodynamics have changed due to a more southern turn off to the sea, causing the development of a larger shadow zone surface area near the dam where sedimentation increases.

The adaptations to the Slufter continue up to 2001 when the Supershoal is formed. The Supershoal is a one by one merging of all shoals in the area. This causes large increases in the surface area and sediment volume of the Supershoal. However, in the period 2009 – 2012 there is still a large increase in surface area and sediment volume. A possible cause for this might be the construction activities of the Maasvlakte 2, but this needs to be further investigated.

The entire ebb tidal delta was aiming for a new equilibrium state before the construction of the Maasvlakte 2. However this was temporarily interrupted in 1989. The foreshore is the main source of sediment for the central part of the delta area, but other sources supply sediment as well.
8. Recommendations

In the scope of this research several issues could not be investigated to solve the research questions and hypotheses. To solve these problems and uncertainties, recommendations for further research are listed below.

1. Investigate the influence of the high sedimentation rate prior to the delivery of the Haringvliet dam.

   In the discussion it was mentioned that the increase in surface area and sediment volume prior to the delivery of the Haringvliet dam in 1970 is probably cause by human interference. Two major constructions were carried out in this time period; the construction of a large land reclamation north of the study area during the sixties of the previous century (Maasvlakte 1) and the construction of the Haringvliet dam itself (1957 – 1970). To investigate the influence of the construction of the Maasvlakte 1 and the Haringvliet dam on the hydrodynamics and sediment transport, is it essential that different scenarios are modelled and investigated. Four different scenarios are suggested:
   a) A scenario where both the Maasvlakte 1 and Haringvliet dam construction are not taken into account
   b) A scenario with solely the presence of the Maasvlakte 1 taken into account
   c) A scenario with solely the construction of the Haringvliet dam taken into account; a decreasing cross-sectional mouth area through time will simulate the different stages of the construction
   d) A scenario with both the Maasvlakte 1 and Haringvliet dam construction taken into account

2. Investigate the influence of the Slufter in the tidal hydrodynamics

   In the discussion the idea of an alteration of the tidal hydrodynamics due to the presence of the Slufter was submitted. The presence of the Slufter might cause the tidal currents to turn off to the sea more south, creating a larger shadow sedimentation zone near the Haringvliet dam. Modelling studies might contribute to accept or reject this theory.

3. Investigate the influence of the construction of the Maasvlakte 2 on suspended sediment concentrations
In the discussion it was mentioned that the strong increase in sedimentation on the shoals between 2001 and 2012 might have been caused due to increased silt concentrations during the construction of the Maasvlakte 2. In the report of effects on the environments (in Dutch: Milieu Effecten Rapport, MER) it was said that the construction of the Maasvlakte 2 might increase the suspended sediments in the area, which might be transported towards the south. However, this effect was investigated prior to the construction and thus is a prediction. Further research might give the confirmation if this is what really happened. If monitoring data is available, measured suspended sediment concentrations of the time period 2008 – 2013 could be requested.

4. Investigate how the system develops after 2001
   As it was mentioned in the discussion (section 6.2.5), more future bathymetric data is needed to reconstruct the development of the morphological units in the area. If this data becomes available, it could be added to the results of this research.
References


**Tools**

Kustviewer, Rijkswaterstaat; Deltares; Nelen & Schuurmans

[http://test.kustviewer.lizard.net/kml/](http://test.kustviewer.lizard.net/kml/).

**Personal communication**

L. Hoek, Rijkswaterstaat (WNZ), oral communication, 6 November 2013, Westraven, Utrecht

A. van der Spek, Deltares, oral communication, 25 November 2013, Deltares, Utrecht
Appendix

1. Numbering of the shoals
2. Presence of the shoals for each time step
3. Numbering of the channels
4. Presence of the channels for each time step
1. Numbering of the shoals

Figure A1.1: Shoals above NAP -2.2 m in 1964.
Figure A1.2: Shoals above NAP -2.2 m in 1968.
Figure A1.3: Shoals above NAP -2.2 m in 1970.
Figure A1.4: Shoals above NAP -2.2 m in 1972.
Figure A1.5: Shoals above NAP -2.2 m in 1976.
Figure A1.6: Shoals above NAP -2.2 m in 1979.
Figure A1.7: Shoals above NAP -2.2 m in 1980.
Figure A1.8: Shoals above NAP -2.2 m in 1984.
Figure A1.9: Shoals above NAP -2.2 m in 1986.
Figure A1.10: Shoals above NAP -2.2 m in 1989.
Figure A1.11: Shoals above NAP -2.2 m in 1990.
Figure A1.12: Shoals above NAP -2.2 m in 1991.
Figure A1.13: Shoals above NAP -2.2 m in 1992.
Figure A1.14: Shoals above NAP -2.2 m in 1996.
Figure A1.15: Shoals above NAP -2.2 m in 1998.
Figure A1.16: Shoals above NAP -2.2 m in 1999.
Figure A1.17: Shoals above NAP -2.2 m in 2001.
Figure A1.18: Shoals above NAP -2.2 m in 2003.
Figure A1.19: Shoals above NAP -2.2 m in 2006.
Figure A1.20: Shoals above NAP -2.2 m in 2009.
Figure A1.21: Shoals above NAP -2.2 m in 2012.
## 2. Presence of the shoals for each time step

Table A2.1: Presence of the shoals for each time step

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“a” en “b” indicate splitted parts

I = Hinderplaat

II = Northern Garnalenplaat

III = Southern Garnalenplaat

IV = new shoal coming from the south-west

V = Supershoal
3. Numbering of the channels

Figure A3.1: Channels below NAP -5 m in 1968.
Figure A3.2: Channels below NAP -5 m in 1970.
Figure A3.3: Channels below NAP -5 m in 1972.
Figure A3.4: Channels below NAP -5 m in 1976.
Figure A3.5: Channels below NAP -5 m in 1979.
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Figure A3.17: Channels below NAP -5 m in 2003.
Figure A3.18: Channels below NAP -5 m in 2006.
Figure A3.19: Channels below NAP -5 m in 2009.
Figure A3.20: Channels below NAP -5 m in 2012.
4. Presence of the channels for each time step

Table A4.1: Presence of the channels for each time step

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“a” en “b” indicate splitted parts

I = Rak van Scheelhoek
II = Small channel which is only present in the data of 1970 and 1972
III = Bokkegat
IV = Hindergat
V = Slijkgat
VI = Channel which splits the Hinderplaat in two segments