# The driving mechanisms behind morphological changes in the Western Scheldt mouth area over the past two centuries – a data analysis

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## Besluiten & geleverde bijdrage van het WL

Het mondingsgebied van de Schelde-estuarium is ingrijpend veranderd over de laatste twee eeuwen. Deze studie beoogd om de mechanisms die deze evolutie mogelijks hebben veroorzaakt in kaart te brengen door (vanuit observaties) de historische verandering in bathymetrie te analyseren in relatie tot geometrische en hydrodynamische veranderingen, en menselijke ingrepen. Hiertoe werden historische bathymetrische kaarten gedigitaliseerd en geanalyseerd, alsook de menselijke ingrepen geinventariseerd.
De belangrijkste waargenomen veranderingen in bathymetrie in het gebied zijn de groei (vooral verbreding) van de geul van de Wielingen en een kloksgewijze rotatie (shift) van de banken in het Noordelijk deel van het mondingsgebied. In het estuarien gebied die aansluit op het mondingsgebied (ten westen van Vlissingen en Breskens) is de voornaamste verandering een antikloksgewijze rotatie van de Honte geul waarbij de geul meer noordelijk is komen te liggen. De voornaamste menselijke ingrepen in die periode zijn het inpolderen van het getij basin van Sloe en Braakman. Alle waarnemingen samengenomen op een tijdslijn suggereert een zekere correlatie in deze veranderingen. Additionele analyses zijn echter nog nodig om hardere conclusies te kunnen nemen.
Naast de analyse van de bathymetrische veranderingen is ook een historische analyse uitgevoerd van het getij. Het effect van de waargenomen alternatie in getij-forcering is dan verkennend onderzocht met behulp van een numeriek model (Delft3D).

## Projectleider WL

Tomas Van Oyen
**2**/23/2016

# Abstract

The Western Scheldt mouth area has shown significant changes in morphology over the past two centuries. However, the driving mechanisms behind these changes are not known yet. In this study historical bathymetries of the mouth and the basin, the incoming tide and human interventions, were analyzed, to relate different possible driving mechanisms to morphological changes.

At first, historical bathymetrical maps were digitized and cross-sectional areas and orientations of the different channels were calculated. The most important morphological change in the mouth area was the growth of the Wielingen. This growth is caused by either a changing outflow direction from the basin, or by the preferred channel location as a result of phase differences between tidal water levels and flow velocities, and wave action. The changes in the Wielingen resulted in a decrease in channel area of the Scheur and the Deurloo and in a shift of the northern channels towards the north. The western part of the Oostgat deepened after back-barrier dams were built in the Eastern Scheldt.

At second, a historical tidal analysis was performed for ten stations along the entire North Sea. It appeared that the incoming tide is related to sea level. Over time the tide has become less flood dominant. A Delft3D model was used to study the effects of the changing tidal asymmetry on sediment transport. This resulted in an increase in sediment transport out of the basin. This did not result in sedimentation on the (proximal part of the) mouth area though.

# Acknowledgements

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# 1. Introduction

Over the past two centuries, the Western Scheldt mouth area has shown significant morphological changes. As can be seen in Figure 1, It has changed from a system with multiple channels and elongated bars, to a system with one major channel in the south, a large shallow area in the middle and several elongated bars and channels in the north. These bars in the north also seem to have changed their orientation from east-west to northeast-southwest.

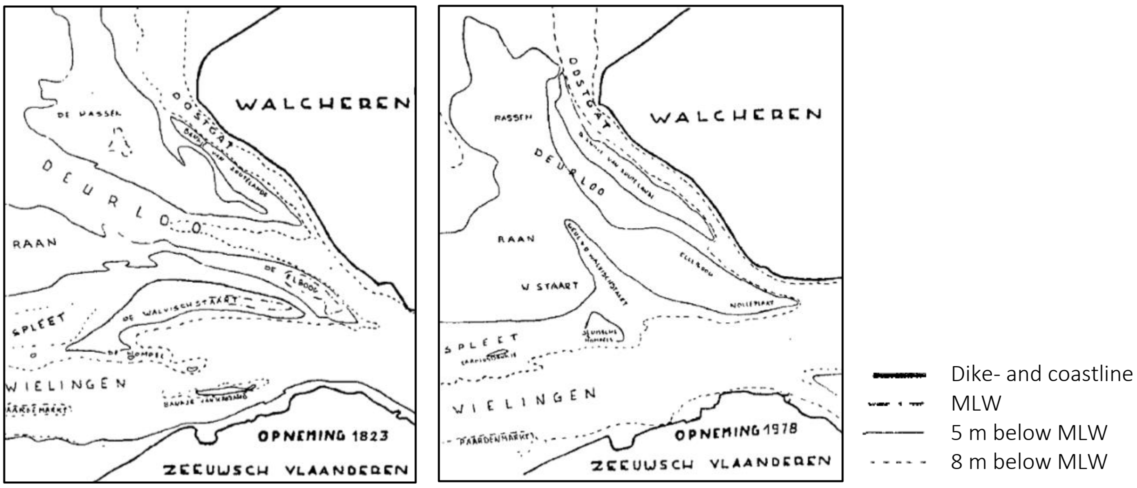


*Figure 1. Morphology of the Western Scheldt mouth based on measurements of the Dienst der Hydrografie, from 1823 (left) and 1978 (right; de Looff en Verhagen, 1986).*

Although these changes are severe, it is not known what has driven them yet. There are several components that are suggested to have influenced the evolution of the mouth area, like:

1. Changes in the geometry of the Western Scheldt basin due to land reclamations;
2. Historical variations in tidal amplitude;
3. Dredging and dumping of sediment in the basin and in the mouth;
4. The construction of the outer harbor of Zeebrugge;
5. The closure of the Eastern Scheldt basin;
6. The construction of groynes and other coastal protection structures along the Belgian and Dutch coast.

Based on existing literature, both the absolute and relative impact of these events are not clear (Van Oyen et al., 2015). Therefore, the objective of this study is to enlarge our understanding of the driving mechanisms behind the morphological changes in the mouth area as previously described. In this chapter the research area will be described and some background will be given, after which a research question will be defined.

## 1.1 Research area

The Western Scheldt is the mouth of the Belgian river the Scheldt. The estuary started to develop around the 12th century, although at that time the Eastern Scheldt was the main outlet of the Scheldt. The Western Scheldt received increasingly more of the Scheldt discharge since the 13th century and the estuary was roughly shaped by the 16th century. In the mouth area there were still some remnants of isles then, but these were gradually cleared. Ongoing land reclamations continued to alter the shape of the estuary until recently (Coen, 1988). Nowadays, the estuary is funnel-shaped, with a width of 800 m in Antwerp and 6 km at Vlissingen, 160 km downstream.

*Figure 2.Bathymetry of the Scheldt mouth (1972) with the names of the major features*

The mouth area is characterized by a sequence of tidal channels and shoals. The main channels are the Oostgat, in the north, and the Wielingen, a large ebb channel in the south (Figure 2). Towards the inlet the Oostgat merges into the Sardijngeul, a flood channel. In the south, the Oostgat is flanked by the shoal: Bankje van Zoutelande, and another channel: the Deurloo. The Wielingen is connected to the Deurloo by the Geul van de Walvischstaart. West of this channel there is a large shoal area: the Vlakte van de Raan. East of the Geul van de Walvischstaart there are two shoals: the Nolleplaat and the Elleboog, that merge into another large shoal area in the west: the Rassen. The Wielingen is partly separated from the coast by the Appelzak, a smaller channel, and the Paardenmarkt, a shoal area.

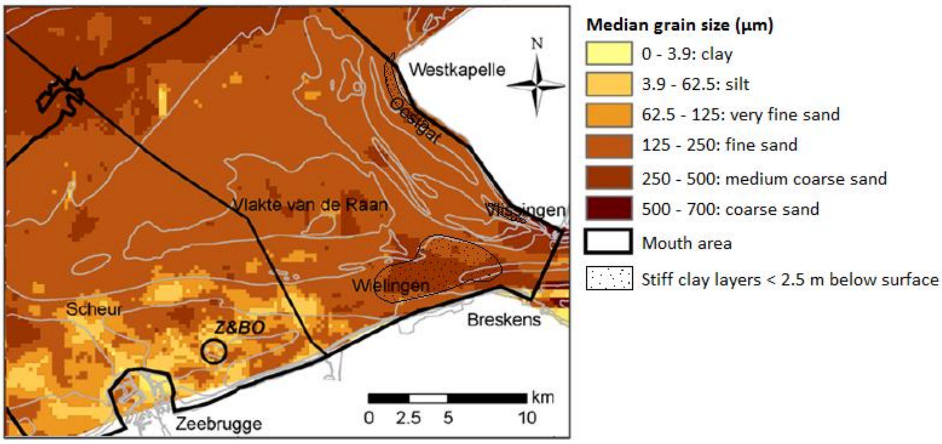


*Figure 3. $D_{50}$ of the sediment in the mouth area (adopted from Du Four, 2006)*

The sediment in the basin mainly consists of fine sand, with a mud fraction of less than 10%, both on the shoals and in the channels. The $D_{50}$ ranges between 0.15 and 0.30 mm. The sediment in the mouth area is more heterogeneous. In the largest part of the area fine sand is found (Figure 3). Near Vlissingen and in the Wielingen coarser sand is found and in the area surrounding Zeebrugge the sediment consists of clay. Furthermore there are stiff clay layers in the subsurface, that at some locations get very close to the surface, as indicated in Figure 3 (du Four et al., 2006). Suspended sediment concentrations in the mouth area are relatively high, with an average of about 200 mgl$^{-1}$ (Terwindt, 1967, Plancke et al., 2014).

## 1.2 Background

### 1.2.1 Hydrodynamics

Since the Middle Ages the Western Scheldt basin has been growing rapidly, which resulted in an increase in tidal prism. At the start of the 17th century the basin area was at its maximum and started decreasing again as a result of land reclamations and sedimentation in the basin. This could lead to a decreasing tidal prism, but the decreasing tidal area was compensated by an increase in tidal range, mainly in the eastern part of the basin (Figure 4). This increase in tidal range was a result of a decreasing intertidal area and therefore a decrease in friction (van Enckevort, 1996). The tidal prism seems to have remained constant since 1800 (van der Spek, 1997; Svašek, 1994). Nowadays, the tidal prism at Vlissingen is about 1100 million m$^3$ and the tidal range is 3.8 m (van der Spek, 1997). Due to tidal asymmetry, the maximum flood velocities are larger than the maximum ebb velocities (Kuijper and Lescinski, 2012).

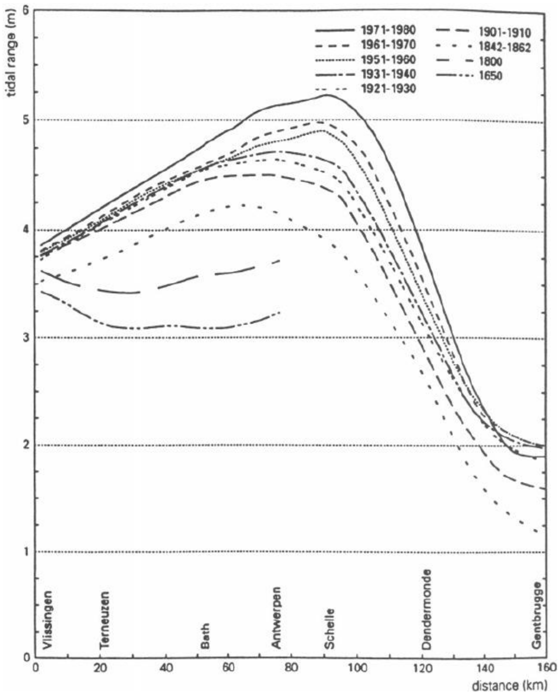


*Figure 4. Tidal range over time, from 1650 to 1980 (van den Berg et al., 1996)*

The incoming tide, the North Sea tide, also seems to have changed since at least 1900. Between 1900 and now, the average relative sea level at Vlissingen has been rising with 2.1 mmyr$^{-1}$. The sea level is rising increasingly fast though: for the period between 1993 and now the relative sea level rise has been 4.1 mmyr$^{-1}$ (Wahl et al., 2013). Pickering et al. (2012) have shown that sea level rise can affect the $M_2$ tidal magnitude in the North Sea. According to Kuijper and Lescinski (2012) the $M_2$ amplitude at Vlissingen has been rising with 0.5 mmyr$^{-1}$ between 1910 and 2010.

In the mouth area the tidal currents are driven by gradients in water level, but also by phase differences within the mouth. The tidal wave in the North Sea propagates in northeastern direction and it takes the wave 1 hour to propagate from the outer delta to Vlissingen or from the outer delta to Westkapelle. Therefore, there is a phase difference of 1 hour between Vlissingen and the western part of the Wielingen, but there is no phase difference between Vlissingen and the western part of the Oostgat. The gradient in the Oostgat is mainly due to a difference in tidal amplitude between Westkapelle and Vlissingen (van Enckevort, 1996b).

Although the Western Scheldt is a macro-tidal estuary and most currents are driven by the tide, waves can be important too. The dominant wind direction in the mouth area is southwest, with an average wind speed of 5 ms$^{-1}$. The wave direction is generally southwest or northwest (Figure 5), with an average wave height of 1-2 m. Normally, the waves break on the coast, but during severe storms they can already break on the Bankje van Zoutelande (Figure 2; Damen, 2014).

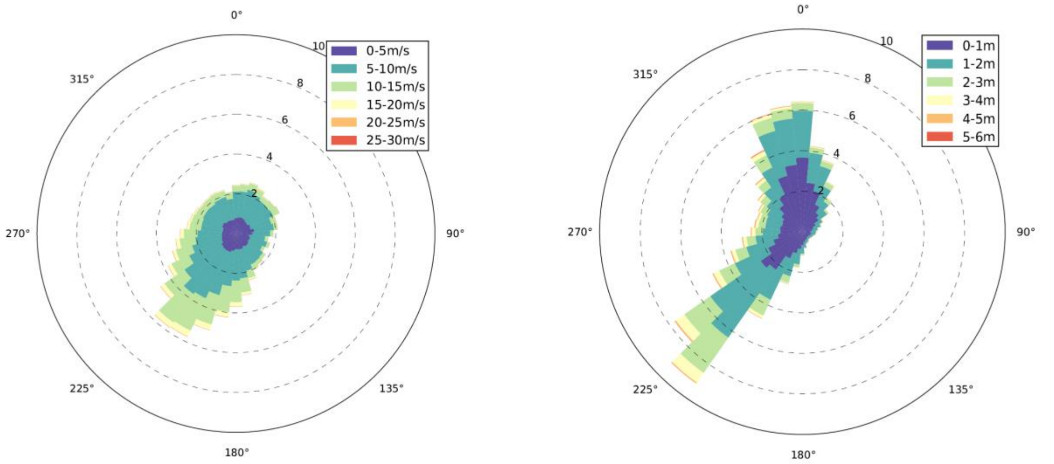
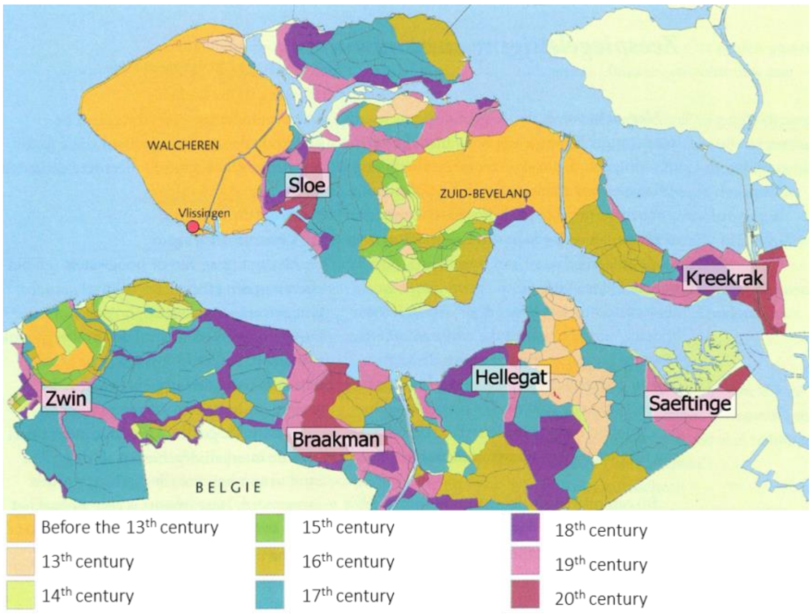


*Figure 5. Left: Measured wind directions and velocities. Radial values are percentages of occurrence; right: Measured wave direction and wave height (Damen, 2014)*

### 1.2.2 Human interventions

#### *Land reclamations*

The most influential human interventions that took place in the Western Scheldt are land reclamations. Since the 13th century this has been an ongoing practice, resulting in a drastic decrease in basin area. Figure 6 shows the areas that have been reclaimed, with the colors indicating the century this happened.



| Decade | Braakman | Sloe | Total |
|---|---|---|---|
| 1810 | 555 | | 1431 |
| 1820 | 474 | 16 | 594 |
| 1830 | 476 | | 679 |
| 1840 | 201 | 80 | 281 |
| 1850 | 723 | 331 | 2461 |
| 1860 | 363 | 187 | 1756 |
| 1870 | 549 | | 1165 |
| 1880 | | | 308 |
| 1890 | 101 | | 528 |
| 1900 | 381 | | 1192 |
| 1910 | 277 | | 801 |
| 1920 | 558 | | 713 |
| 1930 | | | 389 |
| 1940 | | | 0 |
| 1950 | 1525 | 481 | 2006 |
| 1960 | | | 0 |
| 1970 | | 200 | 200 |
| 1980 | | | 890 |
| ***Total*** | ***6183*** | ***1295*** | ***15394*** |

*Figure 6. Left: land reclamations along the Western Scheldt (Vroon et al., 1997), right: reclaimed area near the mouth (Braakman, Sloe), and total area reclaimed (including Zwin, Saeftinge, Kreekrak and Hellegat) in ha*

A lot of land was already reclaimed before 1800. In the past two centuries, reclamations took place at the Sloe and the Kreekrak, resulting in the separation of the Eastern and Western Scheldt, and at Saeftinge, Hellegat, Zwin and Braakman. Figure 6 also shows a more detailed timeframe of the reclamations at the Braakman and Sloe (Vroom et al., 1997).

#### *The harbor of Zeebrugge*

The harbor of Zeebrugge is located approximately 20 km seaward of the inlet of the Western Scheldt. With its 3 km long arms it could influence the alongshore sediment transport towards the Western Scheldt. The arms were built between 1896 and 1907 and extended between 1970 and 1987.

#### *The Eastern Scheldt storm surge barrier*

After a major storm in 1953 it was decided to close off the Eastern Scheldt, with a permeable dam. They started in the 1960's by closing off parts of the Eastern Scheldt basin with so-called back-barrier dams. This resulted in an increase in tidal prism and tidal range in the Eastern Scheldt. The construction of the storm surge barrier started in the 1970's and was completed in 1986. The barrier is open for tide, but can be closed during storm surges. The construction of this storm surge barrier resulted in a drop in tidal range and tidal prism in the Eastern Scheldt (Eelkema, 2013).

#### *Coastal protection*

Along most parts of Walcheren there have been groynes of wooden poles for coastal protection since the beginning of the 18th century. Westkapelle and Vlissingen are protected with dikes. The coastal protection at Walcheren is supplemented with beach nourishments since the 1950's (van der Slikke, 1997). The coast of Zeeuws-Vlaanderen is protected with dikes along the entire coast, of which the last was finished in 1872. Renovation of the dikes took placed in 1953. The dikes at Zeeuws-Vlaanderen are covered in sand and there have been large-scale beach nourishments between 1977 and 1979 (van der Slikke, 1997). Moreover, there are 84 groynes, that were built in the 19th century, to protect Zeeuws-Vlaanderen (Verhagen & van Rossum, 1989). The Belgian coast is protected with groynes that were built between 1900 and 1930 and a large dike between Zeebrugge and Zwin, built in 1867 (van der Slikke, 1997).

#### *Dredging and dumping*

The first dredging in the Western Scheldt took place in 1905 near Bath. Over time the dredging increased and the dredging activities expanded towards the west. The total amount of sediment that was dredged and deposited was first recorded in 1955 (Parée, 2002). The first major enlargement of the shipping channels took place between 1970 and 1975. This enlargement focused on the east of the basin. The dredged sediment was for a large part dumped back into the basin, in the secondary channel – the channel that is not the fairway – and the other part of the sediment was being mined. Before this major enlargement the average amount of sediment that was dredged each year was about 4.5 $Mm^3$ and this increased up to 14 $Mm^3$ per year in 1975 (Liek, 2013). After 1976 there was maintenance dredging of about 9.5 $Mm^3$ per year, until the second major enlargement in 1997 (Parée, 2002). Again, 14 $Mm^3$ was dredged and afterwards maintenance dredging was needed as well (Liek, 2013).

### 1.2.3 Morphological changes in the mouth area

The total sand volume in the proximal part of the mouth has decreased between 1804 and 1931, which resulted in a deepening of the channels and the disappearance of shoals. This deepening of the mouth area is attributed to the increase in tidal prism between the Middle Ages and the 17th century. It took some time for the channels to adjust to the increasing tidal prism, possibly because of flow resistant layers in the subsoil (van Enckevort, 1996b).

#### *Wielingen, Deurloo & channel of the Walvischstaart*

The Deurloo used to be the main ebb channel in the mouth, but it has become shallower since the Middle Ages. The Wielingen, on the other hand, became deeper. In the 17th century the Wielingen reached the same size as the Deurloo and it continued growing after that. In the 19th century, the Wielingen was closer to the coast than nowadays and it consisted of multiple channels. It took until the 1960's before the Wielingen turned into one large channel (van der Slikke, 1997).

The Deurloo did not only become less deep, it also changed its orientation, from east-west to northeast-southwest. This might be due to the decreasing discharge through the Deurloo, resulting in an increase in the relative importance of the North Sea tide (van Enckevort, 1996b). The channel of the Walvischstaart started to grow around 1895. It has a NNW-SSE orientation and is ebb-dominated. The shoal that arose at the end of the channel pushed the Deurloo further towards the north (van Enckevort, 1996b).

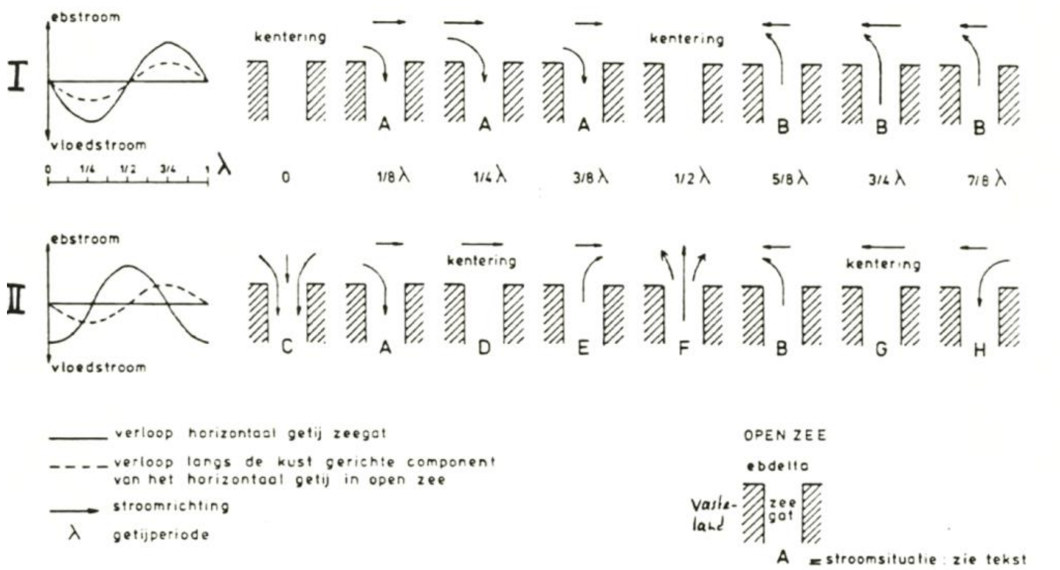


*Figure 7. Sketch of the flow pattern during one tidal period for I) no phase difference between open sea and the basin, and II) a phase difference of ¼ tidal period (Van den Berg, 1987)*

The redistribution of the tidal volume over the channels can be explained by a theory of van den Berg (1987). According to van den Berg, the location of the main channels depends on the phase difference between the tidal wave at open sea and in the basin. As can be seen in Figure 7 the main channel has a preferred orientation when there is no phase difference between the tide at open sea and the tide in the basin. There is no preferred orientation when there is a phase difference of ¼ period.

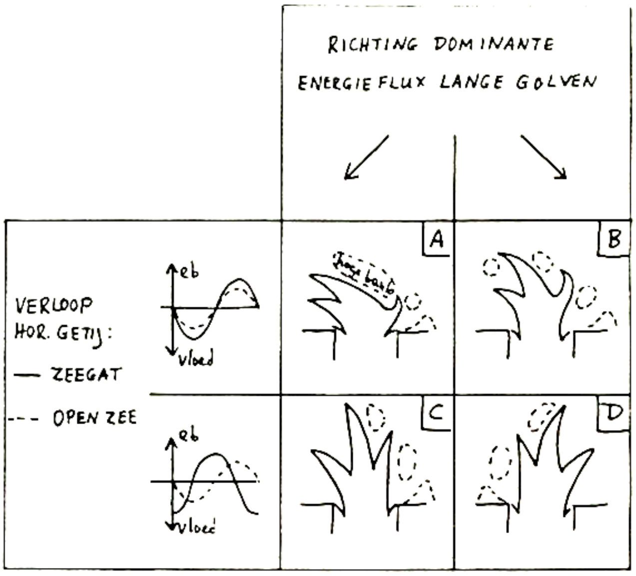


*Figure 8. Sketch of ebb-tidal delta morphology for different tidal and wave conditions (Van den Berg, 1987)*

In the Western Scheldt the phase difference is 3 hours, so according to this theory there would be no preferred orientation of the channel. However, van den Berg (1987), mentions that in this case the orientation of the main channel is determined by the direction of the incoming waves (fFigure 8).

That the main channel has not always been in the south is explained by van den Berg (1987) by the geology. Isles made of stiff clay were in the way of the Wielingen before and it took long before these were eroded. The flow direction out of the estuary might also have influenced the deepening of the Wielingen. The flow direction at the inlet changed from WNW tot WSW. However, according to Enckevort (1996b), it is unclear whether this is a cause or effect.

The changing orientation of the Deurloo is also explained by van den Berg (1987). He reasons that as the ebb flow got more concentrated in the Wielingen, the cross-shore tide in the Deurloo weakens and the longshore tide then becomes relatively more important. In the case of the Western Scheldt this means that flow situation H in Figure 7 becomes more pronounced (van den Berg, 1987).

### *Oostgat*

The water flow in the Oostgat is mainly due to differences in tidal phase and amplitude between Vlissingen and Westkapelle, causing a gradient in water level during high and low water. The Oostgat is a flood dominant channel, receiving a quarter of the total ebb/flood volume. It has been migrating towards the coast, but it is obstructed by coastal defenses (van der Slikke, 1997). The Oostgat is also shifting towards the east (van Enckevort, 1996b).

### *Appelzak*

Until 1894 the Appelzak was a flood channel that barely changed, but around 1930 the western part disappeared and the eastern part became much shallower, probably because of the construction of the harbor of Zeebrugge (uit den Bogaard, 1991). It also changed into an ebb dominated channel (Trouw et al., 2015). Since the beginning of the 20th century the Appelzak did not only shallow, it also moved onshore and it is shifting to the east (Trouw et al., 2015).

### *The shoals*

The Rassen has been decreasing since 1800, because of the movement of the Deurloo towards the north, but the location of the Rassen has always been quite stable (van Enckevort, 1996b). The Rassen used to be connected to the Bankje van Zoutelande, but around 1970 this connection is broken by the development of the channel of the Rassen. A connection between the Rassen and the Elleboog than arise (van der Slikke, 1997). The Elleboog used to be connected with the Vlakte van de Raan and the Nolleplaat. The connection with the Vlakte van de Raan is being broken at the end of the 19th century, when the channel of the Walvischstaart starts to grow (van der Slikke, 1997). The Sluissche Hompels used to be an elongated shoal, with an E-W orientation in the Wielingen. From 1880 on this shoal moved towards the northwest (van Enckevort, 1996b). The Bankje van Zoutelande has been relatively stable, it only expanded towards the east, just like the Oostgat (van Enckevort, 1996b).

### *Distal part of the mouth area*

Haring (1955) studied the distal part of the mouth area, for which he shows there was a net deposition of sediment between 1872 and 1955. For that same period Uit den Bogaard (1991) shows that there was net deposition in the estuary and erosion of the proximal part of the ebb-tidal delta.

### 1.2.4 Morphological changes in the basin

Due to land reclamations the geometry of the Western Scheldt basin has changed significantly since the 13th century (Figure 6), which caused a lot of morphological changes in the basin. Figure 9 shows the bathymetry of the basin between 1800 and now.

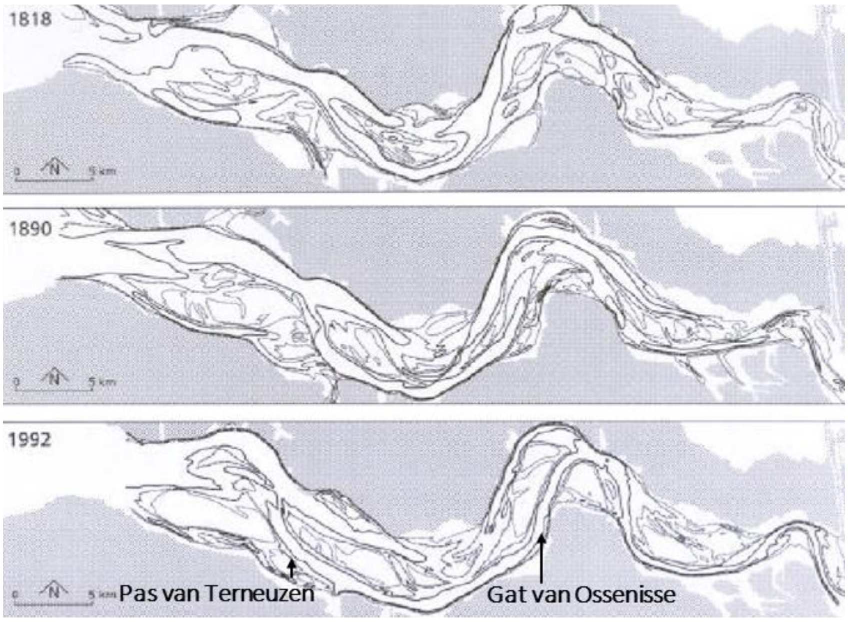


*Figure 9. Channel evolution in the Western Scheldt basin (Jeuken, 2000)*

Figure 10 shows that the amount of channels that develops in an estuary, depends on the width and the depth. Before 1800, the width of the estuary was constantly changing, but after 1800, the width at the inlet (Vlissingen) did not change anymore, and the width of the rest of the estuary was stable enough for the two-channel system as we know it now to develop. The flood channels tend to be rather straight, whereas the ebb channel meanders through the estuary. After 1800, when the ebb channel became more pronounced, the channels bends started migrating with 20 to 80 myr$^{-1}$, until they reached the diked edges. From 1905 on the channel system remained more or less the same (Jeuken, 2000). As the two channels started to develop, the Pas van Terneuzen shifted 2 km downstream. Another channel that has shown substantial changes is the Gat van Ossenisse: it developed from a minor channel, to a channel that now is the main shipping channel (Coen, 1988).

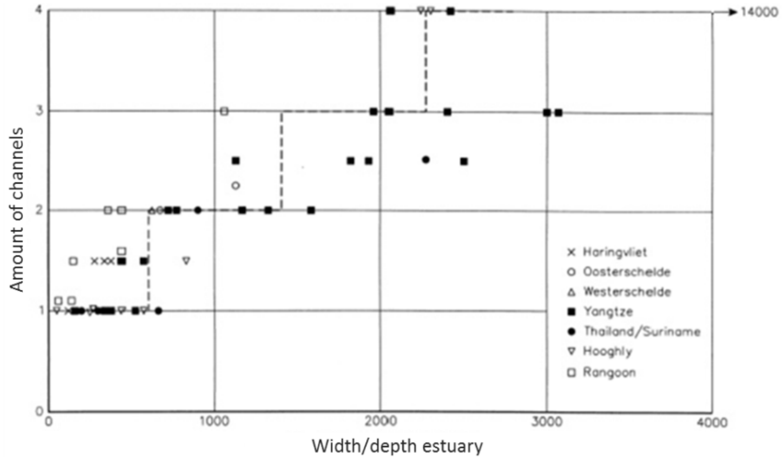


*Figure 10. Amount of channels over the width-depth ratio for different estuaries (Allersma, 1994)*

The basin has been importing sediment since 1878, which is mainly due to the land reclamations. The sediment needed for this originates from the ebb tidal delta (van Enckevort, 1996b). The sediment import has increased between 1970 and 2002, but the reason for this is unknown (Bolle et al., 2010). In the same period the mouth area turned from a strongly importing system to an exporting system (Bolle et al. 2010). Elias and van der Spek (2015) found that the sediment that is imported is mainly mud and that for sand there is even an export.

## 1.3 Aim of this study

In other studies there are thus already some hypotheses proposed for the driving mechanisms behind the morphological changes in the mouth area. An overview of these hypotheses, together with some new ones, is given in Figure 11. The new hypotheses that are added to the ones that are posed in other studies are: 1) The effect of sea level rise on the tidal asymmetry and therefore on sediment transport; 2) The development of the 2-channel system on the mouth morphology; 3) The effect of the rotation of the channels in the basin on the development of the Wielingen.

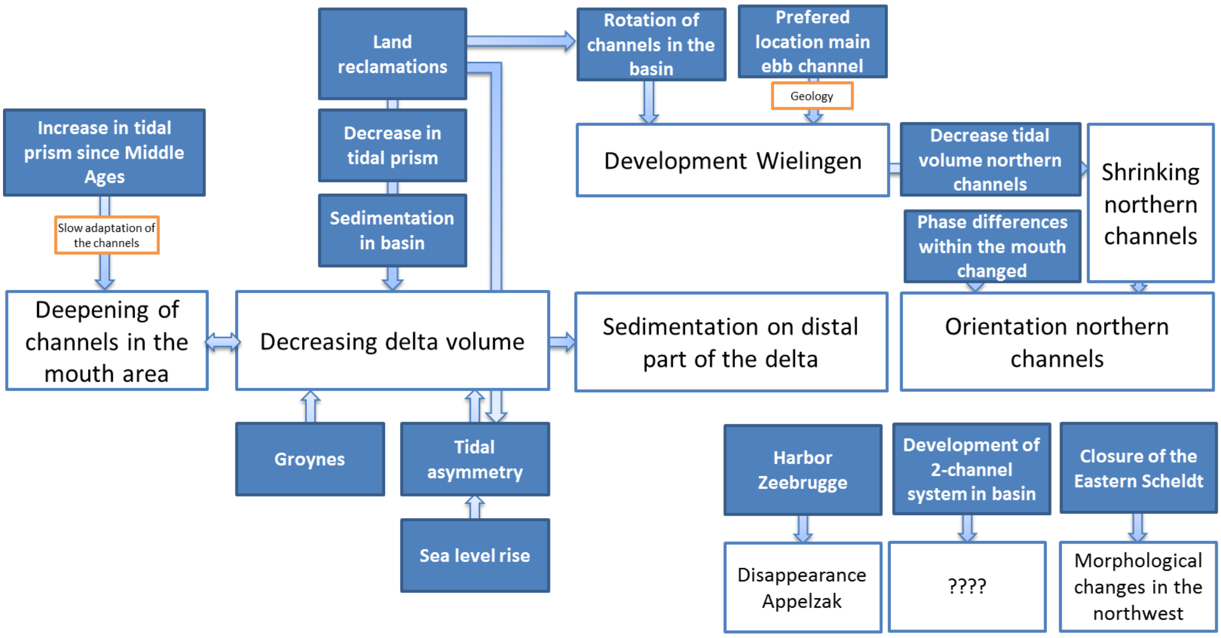


*Figure 11. Possible driving mechanisms (blue boxes) behind changes in the morphology of the mouth (white boxes)*

The aim of this study is to compare the different driving mechanisms with each other and with the morphological changes in the mouth over time. To be able to compare them, the different driving mechanisms and the resulting morphological changes have to described in one parameter that varies over time. Table 1 shows the parameters that are going to be defined, the oldest data that is available for this and whether or not this parameter is already available.

*Table 1. Parameterization of the driving mechanisms and morphological changes*

| Driving mechanism/ morphological change | Parameterization | First data | Parameter available? |
|---|---|---|---|
| Human interventions | | | |
| Land reclamations | Reclaimed area of 1)Sloe; 2)Braakman; 3) Total | Start | Yes |
| Harbor of Zeebrugge | Extended into the sea: yes or no? | Start | Yes |
| Changes in Eastern Scheldt | 1) Start of construction back-barrier dams; 2) Start construction storm surge barrier | Start | Yes |
| Groynes | Amount of groynes at Walcheren and Zeeuws-Vlaanderen | Start | Yes |
| Dredging and dumping | Amount of material dredged | 1955 | Yes |
| Hydrodynamics | | | |
| Sea level rise (SLR) | Sea level rise at Vlissingen | 1900 | Yes |
| Changes in $M_2$ | Amplitude $M_2$ at Vlissingen | 1900 | Yes |
| Changes in $M_4$ | Amplitude $M_4$ at Vlissingen | 1900 | Yes |
| Tidal asymmetry mouth area | $M_4/M_2$ and $2\phi M_2$-$\phi M_4$ | 1900 | Yes |
| Tidal asymmetry basin | $M_4/M_2$ and $2\phi M_2$-$\phi M_4$ | 1971 | Yes |
| Effect of SLR on tidal asymmetry | Tidal asymmetry compared to SLR | 1900 | No |
| Effect of tidal asymmetry on sediment transport | Sediment transport through inlet | - | No |
| Tidal prism | Tidal prism | Estimates since MA | Limited |
| Wave height | Mean significant wave height | 1985 | Yes |
| Phase differences within mouth | $2\phi M_2$-$\phi M_4$ Vlissingen-Breskens | 1973 | No |
| Morphology | | | |
| Sedimentation in the basin | Sand balance | Start | Limited |
| Development of the 2-channel system | Ebb channel cross-sectional area over the flood channel cross-sectional area | Start | No |
| Deepening of the channels | Cross-sectional area of the channels | | |
| Extension of the distal part of the mouth | Volume outer delta | 1872 | Limited |
| Orientation of the channels at the inlet | Orientation of the channels (°) | Start | No |
| Orientation of the Wielingen | Orientation of the channels (°) | Start | No |
| Size of the channels in the mouth area | Cross-sectional area of the channels | Start | No |
| Size of channels in the basin | Cross-sectional area of the channels | Start | No |

From Table 1 it becomes clear that the main task will be the parameterization of the morphology. To obtain the parameters that are wanted, maps from the mouth and the basin will be digitized and orientations and cross-sectional areas will be defined. From the cross-sectional areas the tidal prism can be estimated. To test the relation between sea level rise and $M_2$ tidal amplitude/tidal asymmetry, the change in $M_2$ tidal amplitude along the entire North Sea will be compared with sea level rise. To study the effect of tidal asymmetry on the morphology of the mouth, the effect of tidal asymmetry on sand import/export is going to be studied, using a Delft3D model.

# 2. Morphological changes in the basin and mouth area

## 2.1. Methods

The first bathymetrical map of the area was made by Beautemps-Beaupré in 1804. After that the Royal Marine measured the bathymetry approximately every 15-20 years. In the early years the measurements were done manually and were randomly distributed over the area. Since the measurements were done for shipping purposes, they are mostly focused on the channels. The insecurities in depth are several decimeters, in location they are tens of meters. After 1960, the bathymetry was measured every two years, with a larger accuracy. The total insecurity is now one to two decimeters in depth and several meters in locations (van Enckevort, 1996a). For this study, maps of around 1800, 1866, 1884, 1900, 1938, 1952, 1972 and 1994 are used (for details, see Appendix 1 – List of maps).

The scanned maps were first georeferenced and digitized in ArcGIS. The digital elevation points were then interpolated using the natural neighbor tool. With this technique the depth of a raster cell is determined as a weighted average of the depths of cells nearby. For a more detailed description of this technique and the georeferencing and digitizing method, see Janssens et al. (2012). The digitized maps are shown in Figure 12 (for enlargements, see Appendix 2 – Digitized maps2).

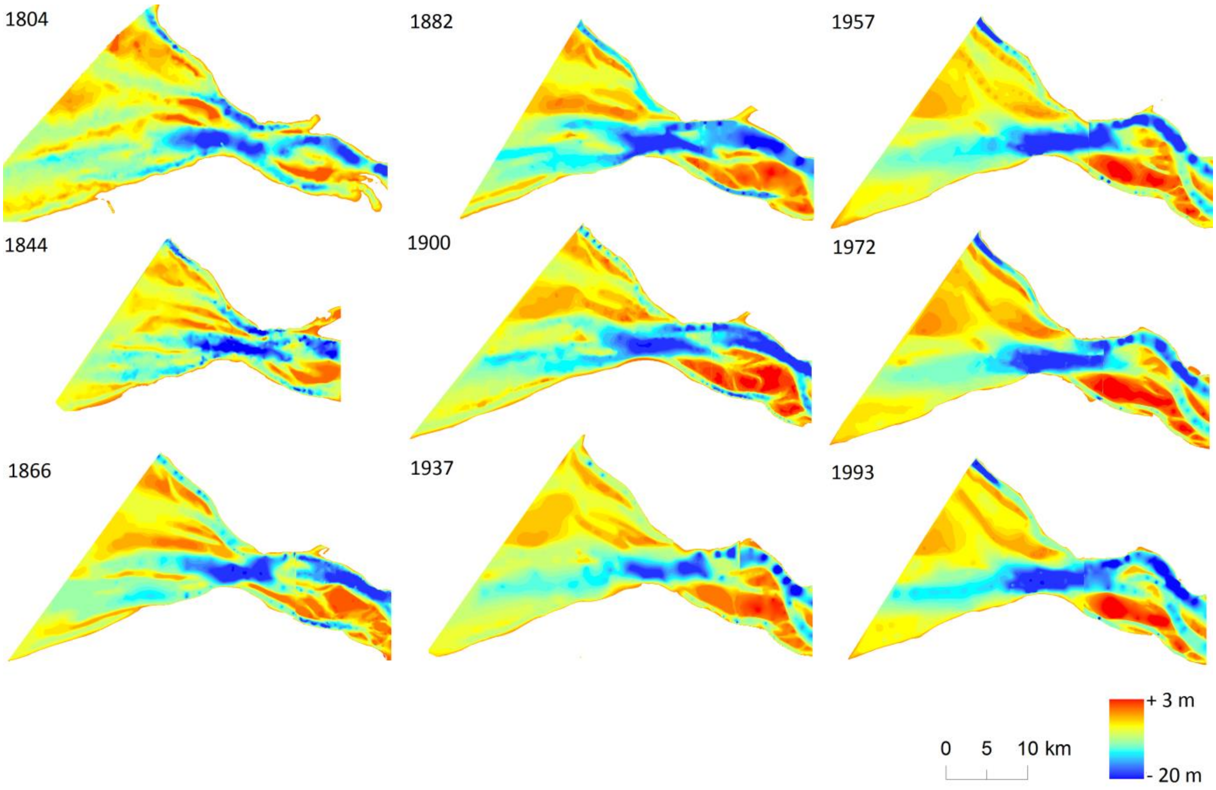


*Figure 12. All digitized maps with depth relative to average low water*

To track the migration of channels over time, the thalweg of the channels was determined. This was done manually, by connecting the deepest points on the maps. The channels were classified as ebb dominant, flood dominant, no tidal dominance or unknown. One could only be sure about the tidal dominance by analyzing the flow velocities in the channels, but flow velocity measurements started only a few tens of years ago. So, for the more recent maps (1994 and 1972), the tidal dominance is based on flow velocities, known from e.g. van Eck (1999) and Van Enckevort (1996b). For the older maps, the tidal dominance is based on the morphology of the channels, after van Veen (1950).

*Figure 13. Flood (left) and ebb (right) channel (Van Veen, 1950)*

Van Veen (1950) identified flood (ebb) channels as channels becoming narrower in the flood (ebb) direction. As an explanation he says that in a flood channel sand is transported in the flood direction and in the ebb direction in an ebb dominated channel. When the two meet, the sand supplied by the two channels will be deposited and a pattern like shown in Figure 13. The result of this identification of the channels is shown in Figure 14 (enlargements in Appendix 3 – Digitized maps3). The uncertainty in the location of the thalweg was determined based on the distribution and the amount of data points. The uncertainty is between 200 and 300 m on each side.

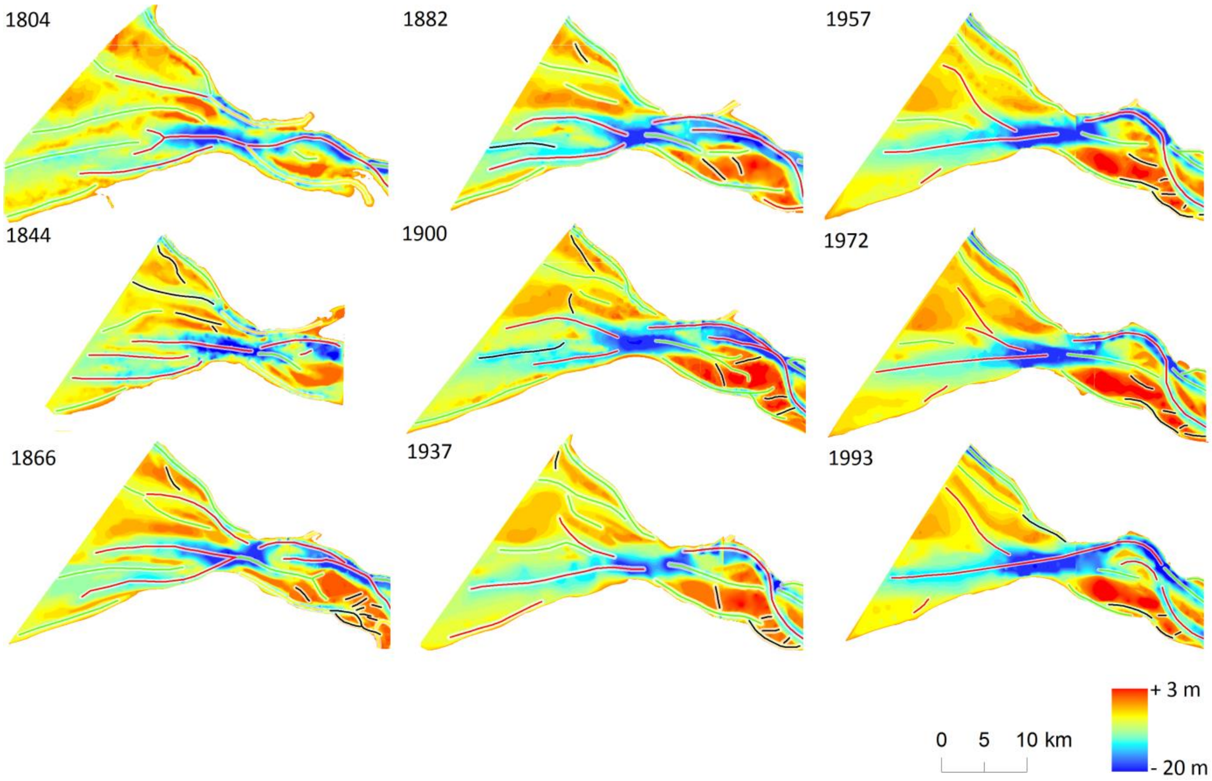


*Figure 14. Channel identification, with ebb channels in red, flood channels in green, channels without preference in yellow, unknown tidal dominance in black and uncertainty band in white*

After the maps were digitized, orientations and cross-sectional areas were calculated for multiple channels. The orientation was determined for the Honte, the main ebb channel in the basin, near the inlet, for the Wielingen and for the Deurloo. For the Oostgat it is assumed that its orientation is stable, because is fixed against the coast of Walcheren.

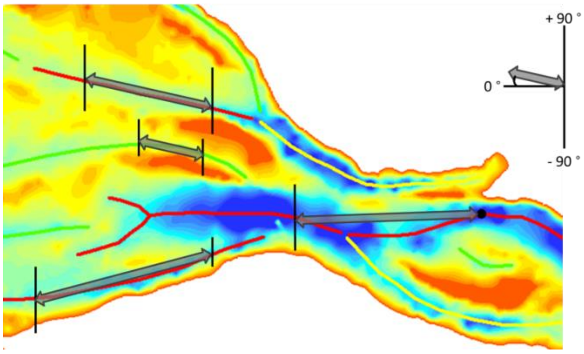


*Figure 15. Locations where the channel orientation is calculated*

To determine the orientation, first the x- and the y-coordinates of the intersections between the thalweg and two fixed north-south lines were determined. Only for the orientation of the Honte one fixed north-south line was used, for the other point the most northern point of the thalweg was used. The location of these lines for the four different channels is shown in Figure 15. The x- and y-coordinates were then subtracted and with these distances the angle between the thalweg and the east-west normal was calculated. When the channel is directed towards north, the angle is positive, when the channel is directed towards the south, the angle is negative.

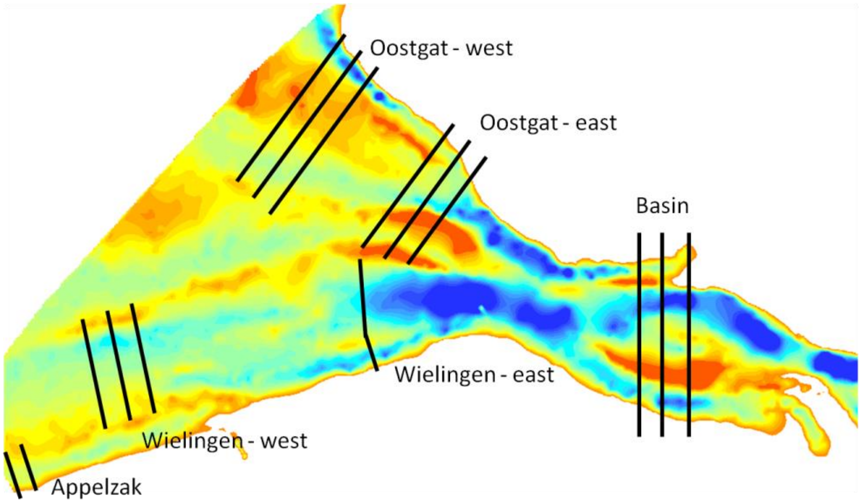


*Figure 16. Locations where the cross-sectional area is calculated*

Then the cross-sectional areas of the channels were determined. This was done for the basin, Oostgat east, Oostgat west, Wielingen east, Wielingen west and the Appelzak. Since the maps are based on interpolation, the cross-sections depend on the presence of a measuring point. The Oostgat, for example, is a narrow channel and if there is no measuring point in the channel in, or very near the cross-section, the depth of the channel will be that of the side walls. To eliminate this, multiple cross-sections have been made for the approximate same location (Figure 16). This was done with the 3D analyst tool of ArcGIS.

In the cross-sections the maxima in bed level were identified to distinguish between the different channels. For each channel the cross-sectional area was then approximated using Riemann sums: by subdividing the area in rectangles and summing the areas of these rectangles.

## 2.2. Results

Figure 17 shows the orientations of the Honte, Wielingen, Geul van de Walvis and the Deurloo over time. The channel of the Walvis and the Deurloo rotated the most; they changed their orientation from east-west to southeast-northwest. The Honte changed its orientation with approximately 20 degrees, changing the inlet from symmetrical into asymmetrical. The orientation of the Wielingen changed a little, especially between 1800 and 1866.

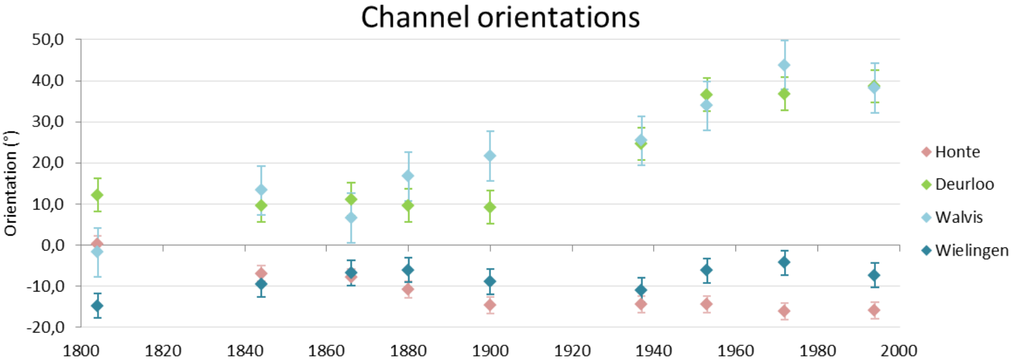


*Figure 17. Channel orientations of the channels in the mouth area*

The changing orientation of the Honte is mainly due to the movement of the most northern point of the thalweg towards the north. As can be seen in Figure 18, the thalweg shifted approximately 2.5 km towards the north between 1804 and 1993.

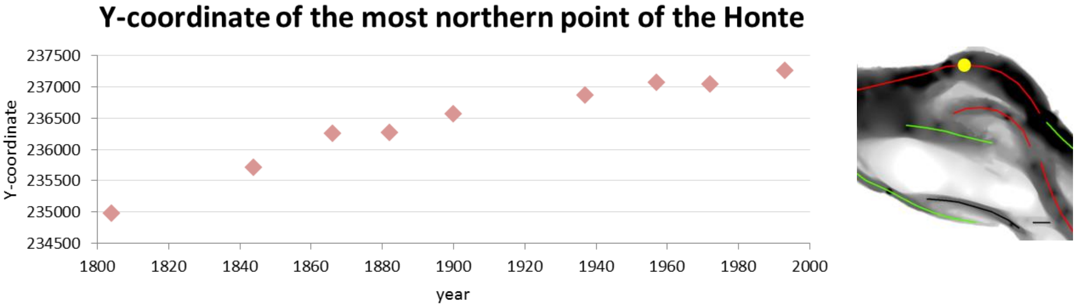


*Figure 18. Location (y-coordinate) of the most northern point (indicated in yellow for 1993 at the right) of the Honte over time*

As the total cross-sectional area at the inlet is related to tidal prism, the cross-sectional area at Vlissingen has been calculated. This has again been done for three cross-sections close to each other, to diminish the error. In addition, this was done for both the maps of the basin and the maps of the mouth, as the inlet is shown on both maps, and averaged again. The result of this is shown in Figure 19. The cross-sectional area at the inlet varies between 60,000 and 67,000 m$^2$, but there is no significant trend of and in- or decreasing inlet area.

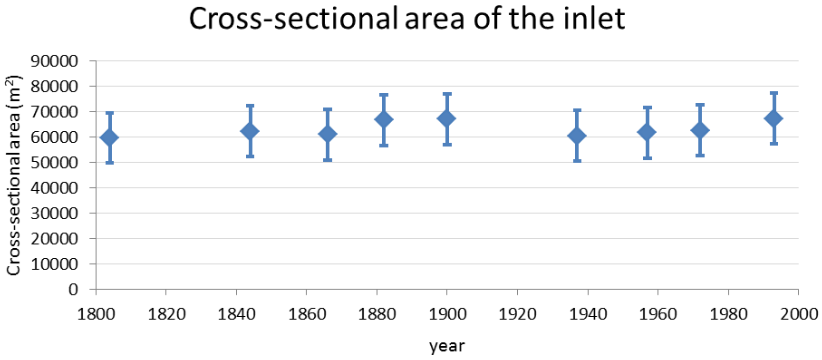


*Figure 19. Total cross-sectional area of the inlet at Vlissingen, averaged over 3 cross-sections*

Figure 20 shows the relative cross-sectional areas of the channels in the basin and in the mouth. For absolute channel areas, see Appendix 4 – Absolute cross-sectional areas4. In the basin, the Sloe has disappeared and the Vaarwater langs de Hoofdplaat has decreased until its area remained stable from 1900/1937 on. The cross-sectional area of the Honte, the main ebb channel, on the other hand, has become relatively larger between 1804 and 1882. Then the Schaar van de Spijkerplaat, the flood channel, started to grow. From 1937 on the relative sizes of the Honte and the Schaar van de Spijkerplaat are stable.

In the eastern part of the mouth, the Wielingen has grown substantially, at the expense of the Deurloo and the Channel of the Walvis/Spleet. The eastern part of the Oostgat is relatively stable. In the western part of the mouth the Wielingen did not increase as much as in the eastern part and the increase was more sudden. Between 1900 and 1937 the relative size of the western Wielingen increased with almost 20 %. Between 1937 and 1957 the Spleet disappeared and the Geul van de Walvis broke through to the west. Moreover the relative size of the Deurloo decreased, whereas the relative size of the Oostgat increased.

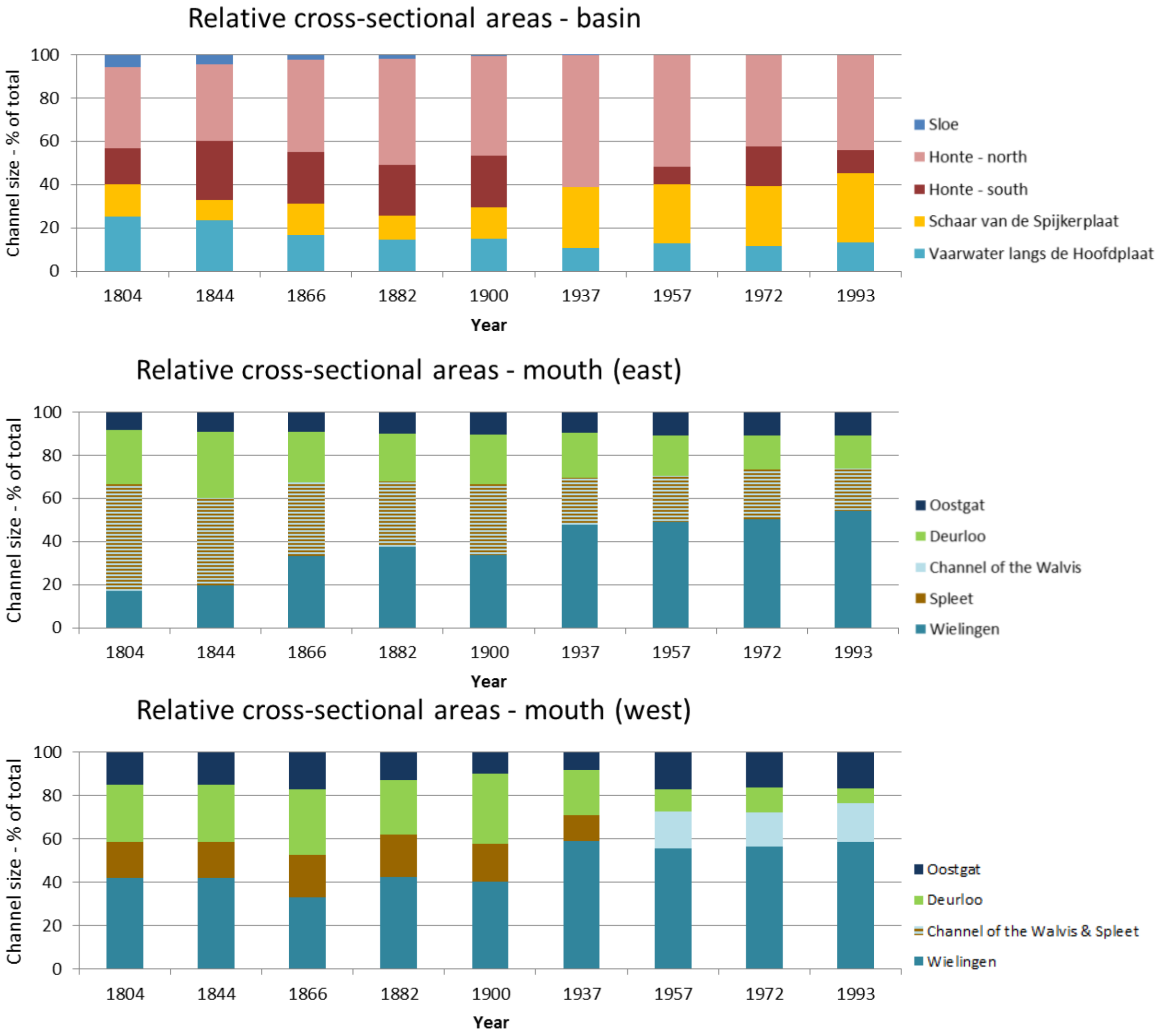


*Figure 20. Cross-sectional areas of the channels in the basin (top) and in the mouth (east: middle; west: bottom) as a percentage of the total cross-sectional area of all channels*

To distinguish between deepening and widening of the channels, Figure 21 shows channel width and the maximum depth of the channels at the locations where the cross-sections were made. From this figure, it becomes clear that the enlargement of the Wielingen is mainly due to a widening of the channel. The Deurloo and the Geul van de Walvis have become both less deep and narrower. In the basin, the Vaarwater langs de Hoofdplaat has become less deep and only became narrower between 1800 and 1866 and the Schaar van de Spijkerplaat has become wider, but kept a constant depth.

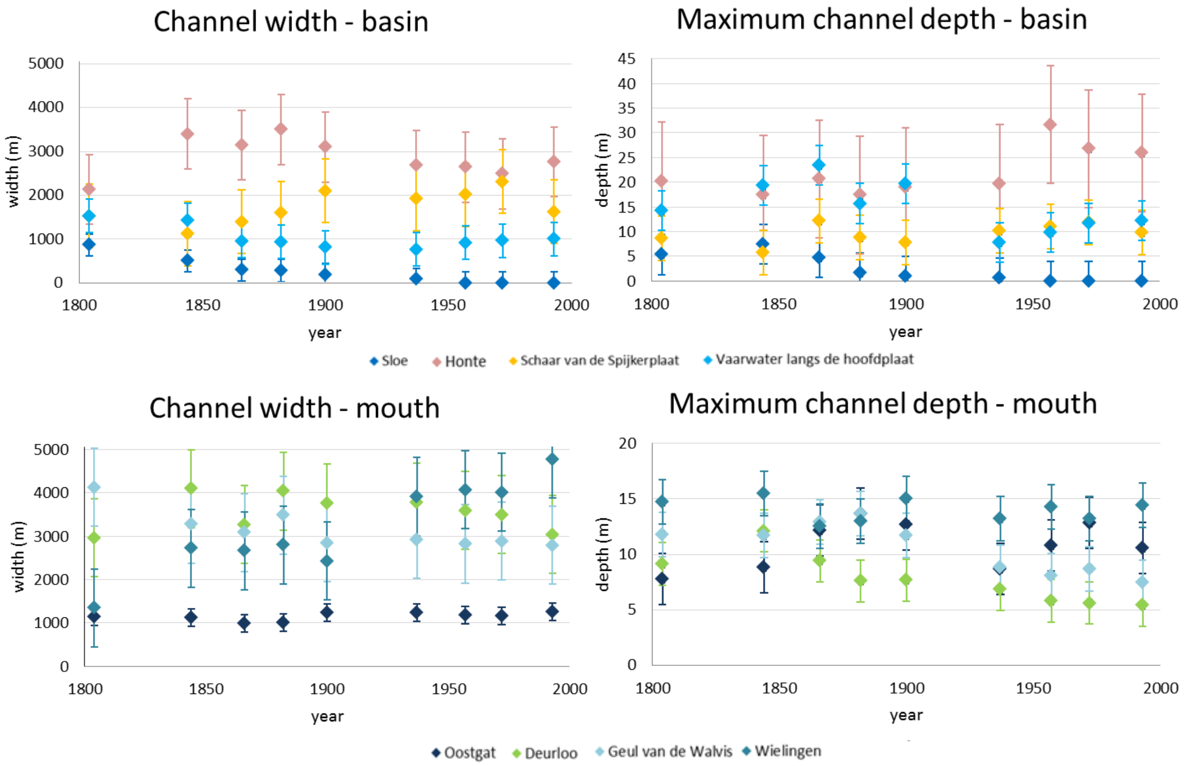


*Figure 21. Width (left) and maximum depth (right) of the channels in the basin (top) and the eastern mouth area (bottom)*

Figure 22 shows the evolution of the Appelzak over time. The cross-sectional area does not show a clear trend, but the channel has become less pronounced. The height difference between the deepest point of the channel and the highest point of the Paardenmarkt has decreased from 7 to almost 0 m.

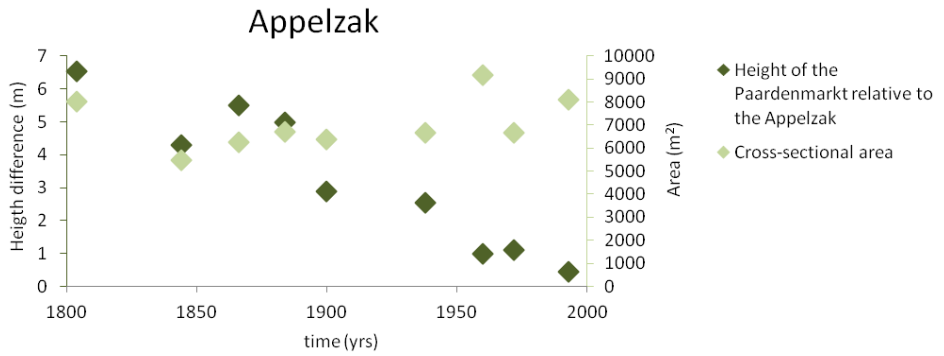


*Figure 22. Cross-sectional area of the Appelzak and the height of the Paardenmarkt over time*

# 3. North Sea tide

## 3.1. Methods

The $M_2$ tidal amplitude has been increasing significantly over the past 100 years. To study the relation between this increasing $M_2$ tide and sea level rise, the behavior of the $M_2$ and the $M_4$ tide in the entire North Sea has been compared to sea level rise. Water level measurements from 5 locations in England (British oceanographic data centre, 2015) and 5 in the Netherlands (Waterbase, 2015) have been used, the exact locations are shown in Figure 23.

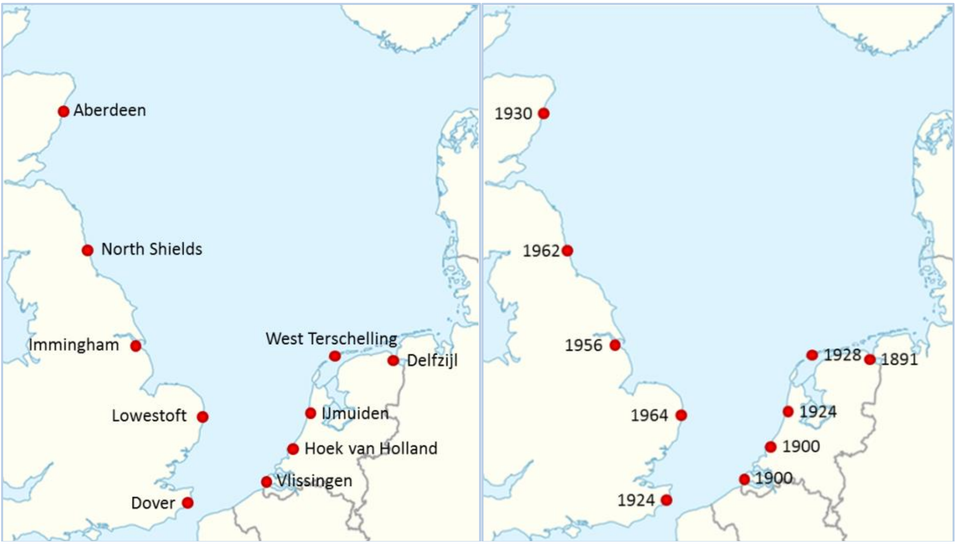


*Figure 23. Locations of which water level measurements have been analyzed (left) and the year the measurements started (right)*

The oldest dataset of water level measurements that is used starts in 1891. Figure 23 shows the years the measurements started for all locations. No datasets shorter than 50 years were used, to be able to analyze long-term trends. For the Dutch stations the water level was measured with an interval of 3 hours until 1971, from then until 1986 it was measured every hour and after that it was measured every 10 minutes. For the English stations, the water level was measured every hour until 1992 and every 15 minutes after that. For IJmuiden water level data until 1983 is used, because after that the tide gauge was allocated, for the other stations data until 2014 is used.

Table 2. Years used for tidal analysis per station and the number of full 18.6-year cycles available

| Station | Years of which data is used | 18.6-year cycles |
|---|---|---|
| Aberdeen | 1930, 1931, 1935, 1936, 1946-1949, 1951, 1957, 1958, 1964, 1965, 1967-1975, 1980-2014 | 3 |
| Delfzijl | 1891-2014 | 6 |
| Dover | 1924, 1926, 1928, 1934-1936, 1938, 1958-1974, 1976-1989, 1991-2009, 2011-2014 | 3 |
| Hoek v Holland | 1900, 1906, 1910, 1911, 1932, 1936, 1939-1946, 1948-2014 | 4 |
| IJmuiden | 1924-1944, 1947-1964, 1966-1983 | 3 |
| Immingham | 1956-1958, 1963-2014 | 3 |
| Lowestoft | 1964-2013 | 2 |
| North Shields | 1962, 1964-1974, 1978-2001, 2003-2014 | 3 |
| Vlissingen | 1900, 1906, 1910-2014 | 5 |
| W Terschelling | 1928-2014 | 4 |

A least squares harmonic analysis was performed after Codiga (2011). Not all years of water level data were suitable for tidal analysis though: at least two weeks of data have to be available to isolate the spring-neap component. To also eliminate weather effects, it was chosen to only use datasets with at least one month of water level data. The resulting years of which data is used are shown in Table 2.

As the data is analyzed per year, the 18.6-year cycle will still be present in the resulting yearly-averaged amplitudes and phases. To determine the change in amplitude or phase, a plural of 18.6 years should be considered. Table 2 shows the amount of 18.6-year cycles that are present in the time series and over which the changes in tidal amplitudes and phases are determined. Changes in amplitudes and phases are determined using a least-squares fit.

## 3.2. Results

In Figure 24 the changes in tidal amplitude for $M_2$ and $M_4$ are shown. The $M_2$ amplitude shows to have been rising in most parts of the North Sea, the only exceptions are Dover and Immingham. The change in amplitude ranges between -2.4 $mmyr^{-1}$ and +1.5 $mmyr^{-1}$. The change in $M_4$ amplitude ranges between -0.4 $mmyr^{-1}$ and +0.5 $mmyr^{-1}$ and is much more spatially variable than the change in $M_2$ amplitude. For the full time series of $M_2$, $M_4$ and $M_6$ amplitude and phase see appendix 5.

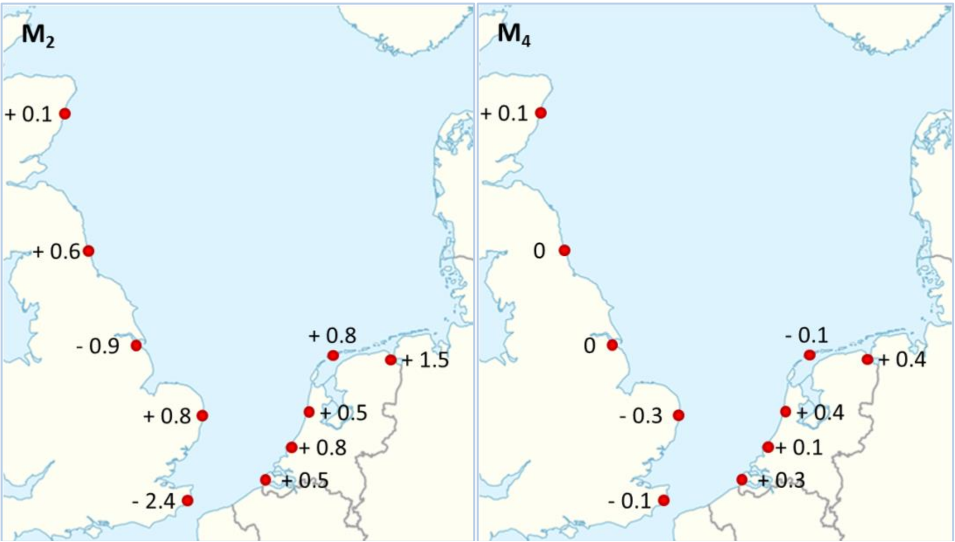


*Figure 24. Maps with changes in amplitude $M_2$ (left) and $M_4$ (right) in $mmyr^{-1}$*

# 4. Tidal asymmetry in the Western Scheldt basin

As seen in the previous chapter, the incoming $M_2$ and $M_4$ tide have changed over the past century. It is likely that the tidal asymmetry has then changed as well. How the tidal asymmetry has changed and how this influenced the sediment transport will be studied in this chapter.

## 4.1. Methods

To study the effect of a changing tidal asymmetry on sediment transport a Delft3D model was used (Nnafie, pers. comm.). An idealized and real geometry (Figure 25) have been used. In the idealized geometry, the width at Westkapelle is 25 km and is exponentially decreasing. The depth in the idealized situation is linearly decreasing from 15 m with a rate of 1 m per 11.6 km. For the real situation, the real geometry has been used, together with the real width-averaged depth.

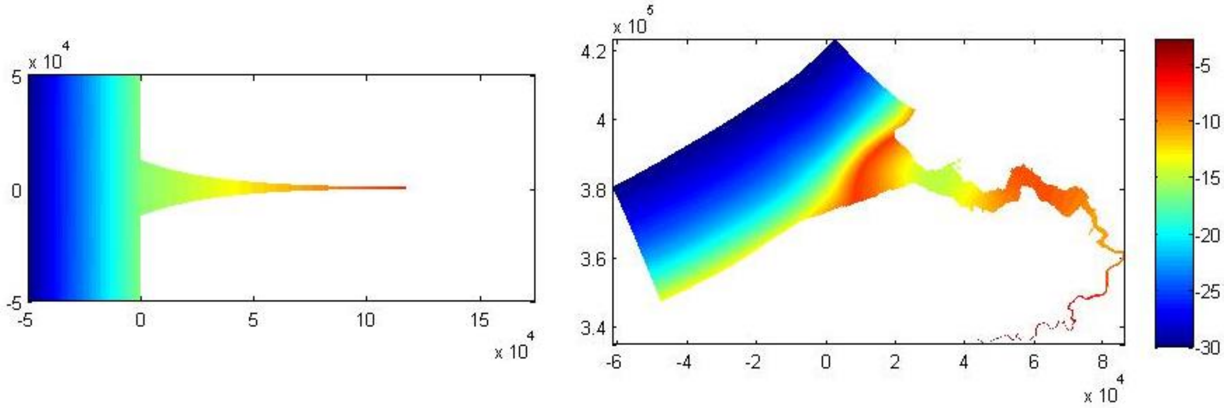


*Figure 25. Idealized geometry and bathymetry (left) and real geometry and bathymetry (right)*

An $M_2$ and $M_4$ driven water level variation was forced on the boundaries. By default the $M_2$ amplitude at the southern boundary was 1.6 m and 1.2 m at the northern boundary. The $M_4$ amplitude was 0.1 m and had a phase of -51° relative to $M_2$. In terms of sediment, the grain size of sand has been used. The hydrodynamics and sediment transport were then calculated for 5 consecutive days. This has also been done for a varying $M_4$ amplitude and phase, to study the effects of a changing tidal symmetry on sediment transport.

The resulting sediment transport through 18 cross-sections (21 for the real geometry) in the basin and in the mouth area was averaged over time and divided over the cross-section width. This cross-sectionally averaged sediment transport was compared to the asymmetry of the incoming tide. To study the evolution of the tidal asymmetry throughout the basin a least-squares harmonic analysis was performed to water levels in the basin (Codiga, 2011).

## 4.2. Results

Figure 26 shows how sediment transport changes if the incoming tide changes. If the amplitude of the incoming $M_4$ tide increases relative to the $M_2$ amplitude, at first the area that imports sediment shifts more landward and the sediment export in the west increases, but for the idealized geometry this is clearer than for the real geometry. For the real geometry the spatial variability of the sediment transport is larger than for the idealized geometry. When it comes to the phase difference between $M_4$ and $M_2$, the sediment export is largest when the phase difference is slightly positive. The basin imports more when the phase difference becomes larger. For the real geometry the spatial variability is larger again.

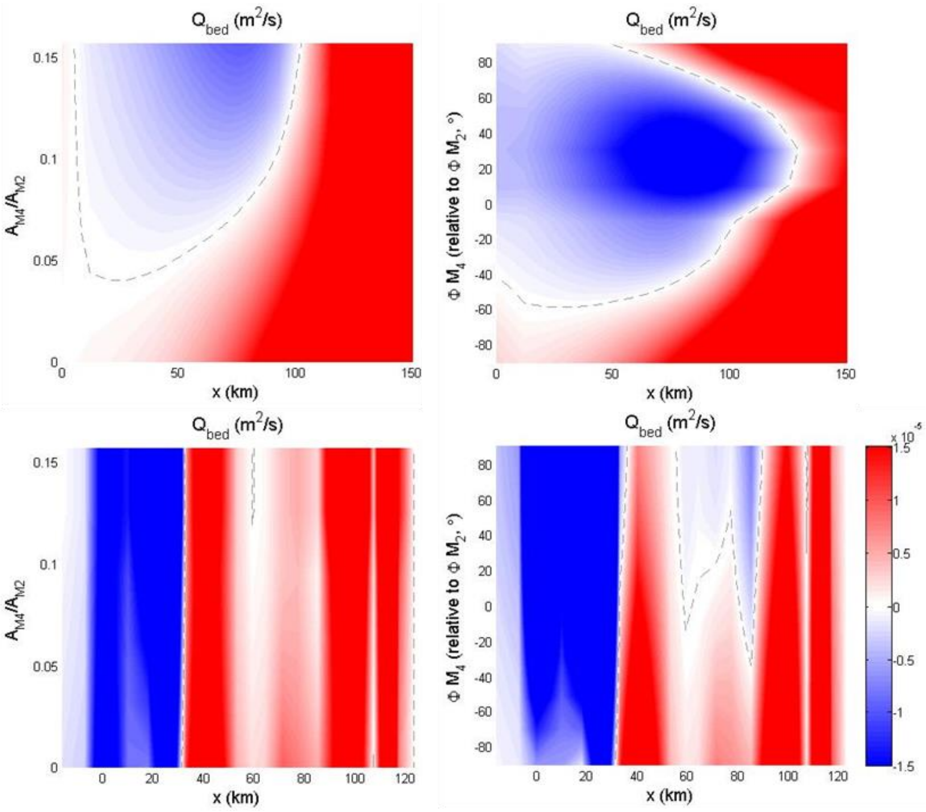


*Figure 26. Cross-sectionally averaged sediment transport over x (x=0 being Vlissingen) and $A_{M4}/A_{M2}$ (left) and the phase of $M_4$ relative to the $M_2$ phase for the idealized geometry (top) and the idealized geometry (bottom).*

The phase differences and amplitudes shown in Figure 26 are the ones that are forced on the southern boundary. **Fout! Verwijzingsbron niet gevonden.** shows the evolution of the amplitudes and phase differences over the estuary for the idealized and real geometry, for the default case (amplitude $M_4$ = 0.1 m, $2\phi M_2 - \phi M_4$ = -51). The phase difference varies over the estuary, explaining the variation of sediment transport over the basin. It can also be seen that the model is able to reproduce the tide as observed in the field, for the real geometry even slightly better than for the real geometry.

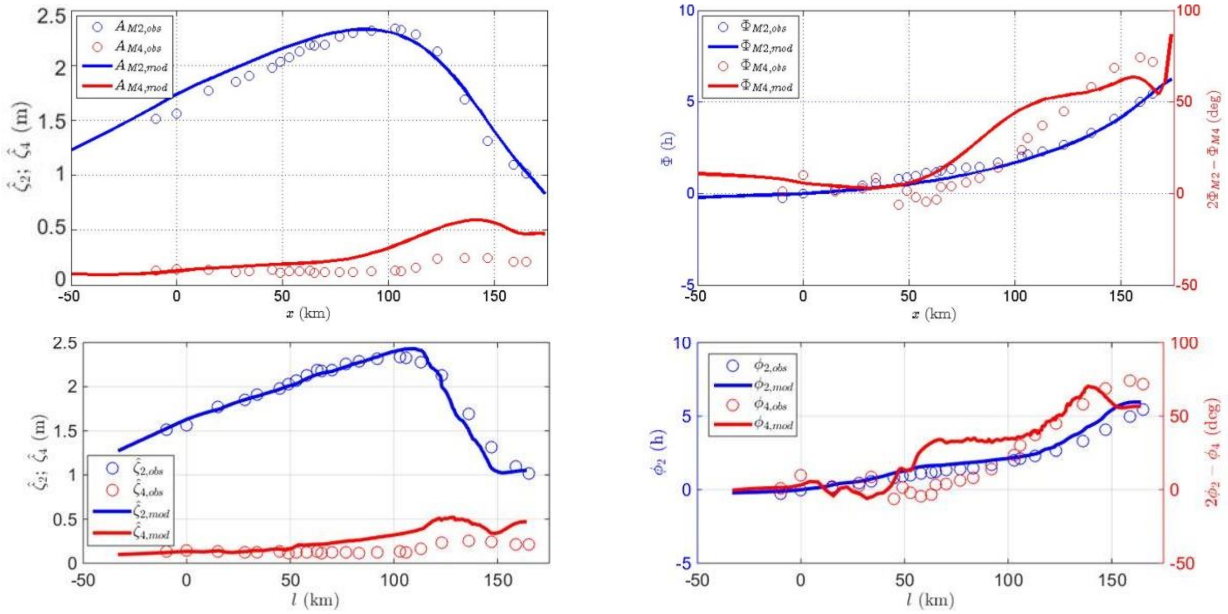
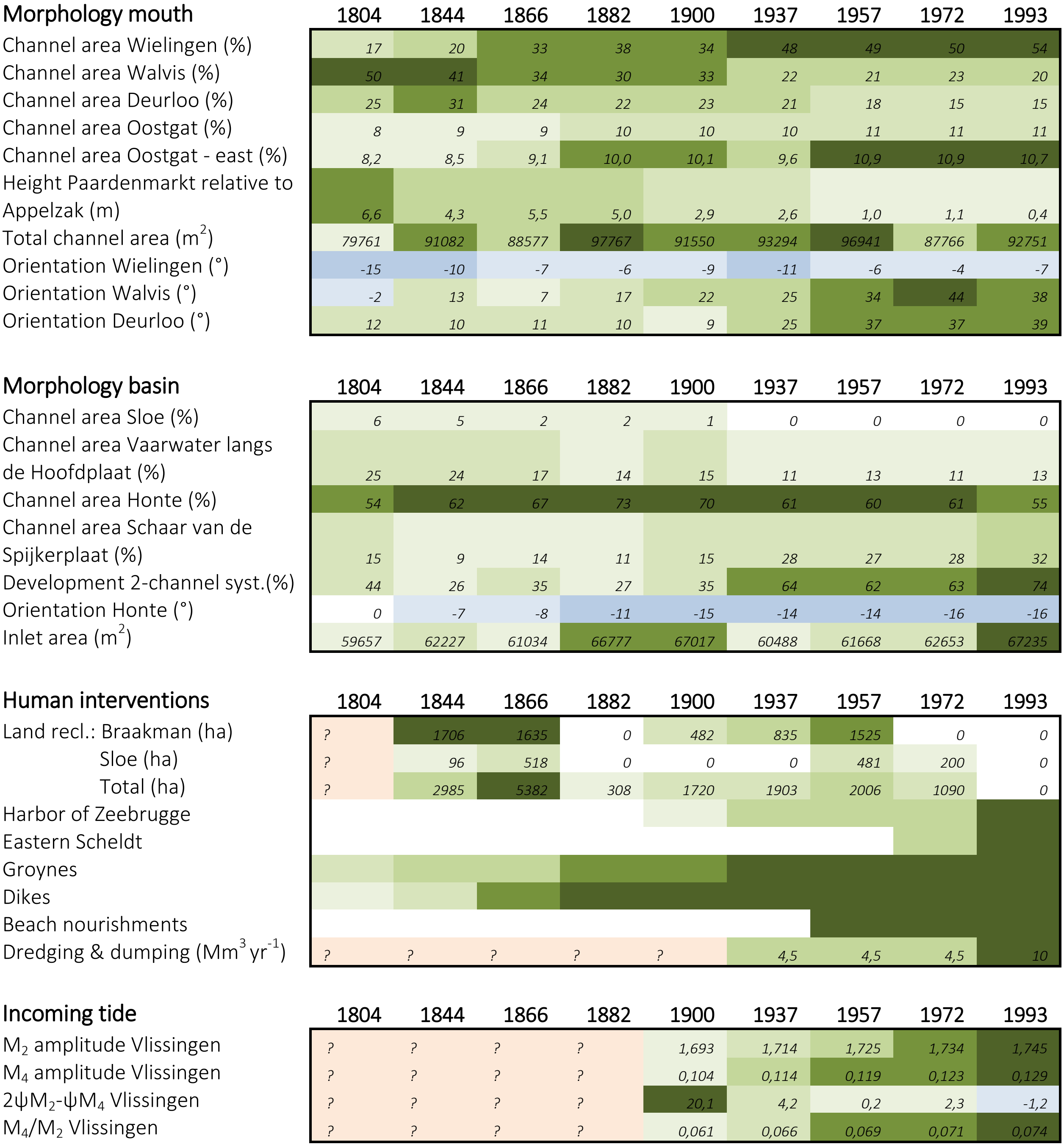


*Figure 27. Amplitude (left) and phase (right) of $M_2$ and $M_4$ throughout the basin for the idealized (top) and the real geometry (bottom). Model results compared to observations.*

# 5. Discussion

In Table 3 all the results are shown over time: at the top the morphological changes are shown, at the bottom the driving mechanisms. The colors are added to make the trends more visual, but they are scaled to the different parameters and do therefore not have unique values. In this chapter, the relation between the morphological changes and the driving mechanisms in time will be discussed.

Table 3. All the morphological changes and driving mechanisms that were studied over time



| Morphology mouth | 1804 | 1844 | 1866 | 1882 | 1900 | 1937 | 1957 | 1972 | 1993 |
|---|---|---|---|---|---|---|---|---|---|
| Channel area Wielingen (%) | 17 | 20 | 33 | 38 | 34 | 48 | 49 | 50 | 54 |
| Channel area Walvis (%) | 50 | 41 | 34 | 30 | 33 | 22 | 21 | 23 | 20 |
| Channel area Deurloo (%) | 25 | 31 | 24 | 22 | 23 | 21 | 18 | 15 | 15 |
| Channel area Oostgat (%) | 8 | 9 | 9 | 10 | 10 | 10 | 11 | 11 | 11 |
| Channel area Oostgat - east (%) | 8,2 | 8,5 | 9,1 | 10,0 | 10,1 | 9,6 | 10,9 | 10,9 | 10,7 |
| Height Paardenmarkt relative to Appelzak (m) | 6,6 | 4,3 | 5,5 | 5,0 | 2,9 | 2,6 | 1,0 | 1,1 | 0,4 |
| Total channel area ($m^2$) | 79761 | 91082 | 88577 | 97767 | 91550 | 93294 | 96941 | 87766 | 92751 |
| Orientation Wielingen (°) | -15 | -10 | -7 | -6 | -9 | -11 | -6 | -4 | -7 |
| Orientation Walvis (°) | -2 | 13 | 7 | 17 | 22 | 25 | 34 | 44 | 38 |
| Orientation Deurloo (°) | 12 | 10 | 11 | 10 | 9 | 25 | 37 | 37 | 39 |

| Morphology basin | 1804 | 1844 | 1866 | 1882 | 1900 | 1937 | 1957 | 1972 | 1993 |
|---|---|---|---|---|---|---|---|---|---|
| Channel area Sloe (%) | 6 | 5 | 2 | 2 | 1 | 0 | 0 | 0 | 0 |
| Channel area Vaarwater langs de Hoofdplaat (%) | 25 | 24 | 17 | 14 | 15 | 11 | 13 | 11 | 13 |
| Channel area Honte (%) | 54 | 62 | 67 | 73 | 70 | 61 | 60 | 61 | 55 |
| Channel area Schaar van de Spijkerplaat (%) | 15 | 9 | 14 | 11 | 15 | 28 | 27 | 28 | 32 |
| Development 2-channel syst.(%) | 44 | 26 | 35 | 27 | 35 | 64 | 62 | 63 | 74 |
| Orientation Honte (°) | 0 | -7 | -8 | -11 | -15 | -14 | -14 | -16 | -16 |
| Inlet area ($m^2$) | 59657 | 62227 | 61034 | 66777 | 67017 | 60488 | 61668 | 62653 | 67235 |

| Human interventions | 1804 | 1844 | 1866 | 1882 | 1900 | 1937 | 1957 | 1972 | 1993 |
|---|---|---|---|---|---|---|---|---|---|
| Land recl.: Braakman (ha) | ? | 1706 | 1635 | 0 | 482 | 835 | 1525 | 0 | 0 |
| Sloe (ha) | ? | 96 | 518 | 0 | 0 | 0 | 481 | 200 | 0 |
| Total (ha) | ? | 2985 | 5382 | 308 | 1720 | 1903 | 2006 | 1090 | 0 |
| Harbor of Zeebrugge | | | | | | | | | |
| Eastern Scheldt | | | | | | | | | |
| Groynes | | | | | | | | | |
| Dikes | | | | | | | | | |
| Beach nourishments | | | | | | | | | |
| Dredging & dumping ($Mm^3 yr^{-1}$) | ? | ? | ? | ? | ? | 4,5 | 4,5 | 4,5 | 10 |

| Incoming tide | 1804 | 1844 | 1866 | 1882 | 1900 | 1937 | 1957 | 1972 | 1993 |
|---|---|---|---|---|---|---|---|---|---|
| $M_2$ amplitude Vlissingen | ? | ? | ? | ? | 1,693 | 1,714 | 1,725 | 1,734 | 1,745 |
| $M_4$ amplitude Vlissingen | ? | ? | ? | ? | 0,104 | 0,114 | 0,119 | 0,123 | 0,129 |
| $2\psi M_2$-$\psi M_4$ Vlissingen | ? | ? | ? | ? | 20,1 | 4,2 | 0,2 | 2,3 | -1,2 |
| $M_4/M_2$ Vlissingen | ? | ? | ? | ? | 0,061 | 0,066 | 0,069 | 0,071 | 0,074 |

## 5.1. The effect of changing incoming hydrodynamics

The tidal asymmetry at Vlissingen shows significant changes since (at least) 1900. Although no direct relation with changes in the morphology of the mouth can be found, it is known from Uit den Bogaard (1991) that the mouth area eroded. In this section the relation between the tidal asymmetry and the import/export of sediment from the basin and the erosion of the mouth area will be discussed.

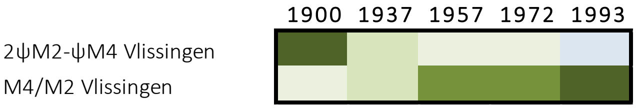


*Figure 28. Change in tidal asymmetry at Vlissingen*

The accuracy of the historical tidal analysis is high, due to the length of the time series. Insecurities are mainly due to the possible allocation of the measuring equipment and improvements of the measuring techniques. The increasing measuring frequency over time did not affect the results of tidal analysis. Time series with high frequencies have been reduced to a 3 hour frequency and analyzed. It appears that the $M_4$ amplitude then only changes with ± 0.45 % and the $M_2$ amplitude even only with ± 0.03 %. Therefore the earlier and the later datasets can be compared without problems.

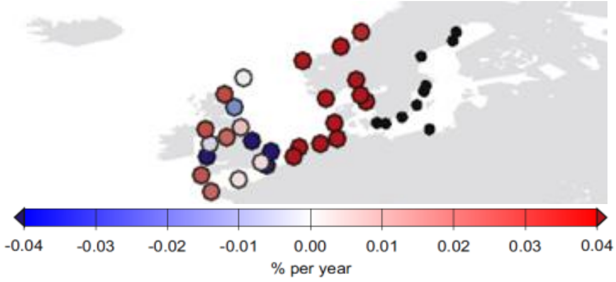


*Figure 29. Increase in $M_2$ amplitude in the North Sea (Woodworth, 2010)*

A study to the change in $M_2$ amplitude was also done by Woodworth (2010). As shown in Figure 29, they found similar trends, although they found a decreasing $M_2$ amplitude for more locations along the English coast. They possibly used longer time series, for which only high and low water levels are available. Moreover, the exact locations they used for their analysis is not clear, so they might have used different datasets.

### 5.1.1. Relation $M_2$, $M_4$ and sea level rise

Changes in $M_2$ and $M_4$ amplitude may have multiple reasons, like local effects of dredging, building of ports, climate changes, including gyre spin up and sea level rise (Pickering et al. 2012). Figure 30 shows the changes in $M_2$ and $M_4$ amplitude compared to the sea level rise at the same location, over the same period. There seems to be a clear relation between sea level rise and $M_2$ amplitude: for most stations the $M_2$ amplitude increases as the sea level rises. There are only a few locations (Dover and Immingham) where the sea level rises, but the $M_2$ amplitude decreases.

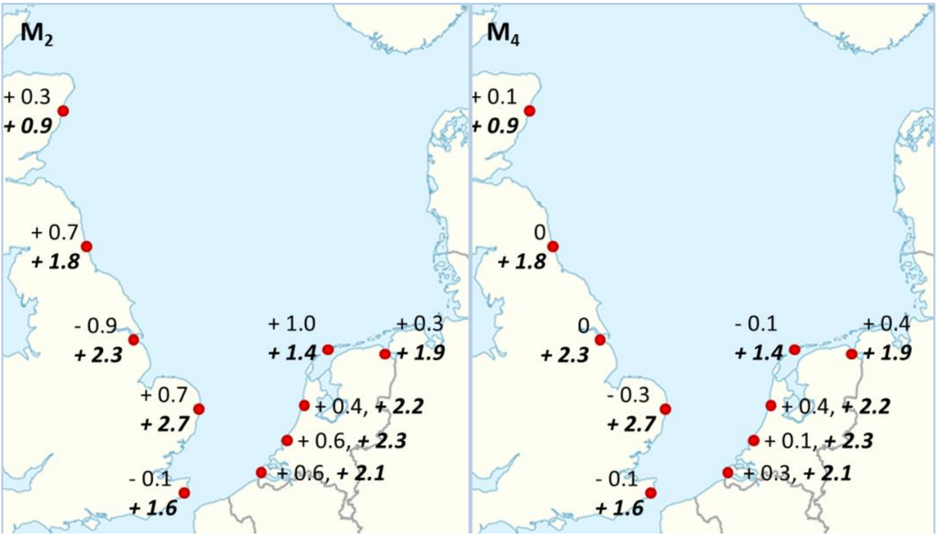


*Figure 30. Change in $M_2$ (left) and $M_4$ (right) amplitude compared to sea level rise (Wahl et al., 2013) for different locations in the North Sea (both in mmyr$^{-1}$)*

These results can be compared to the study of Pickering et al. (2012), who have modelled the effect of sea level rise on the $M_2$ tidal magnitude. Figure 31 shows the change in $M_2$ amplitude that they found for a 2 m sea level rise.

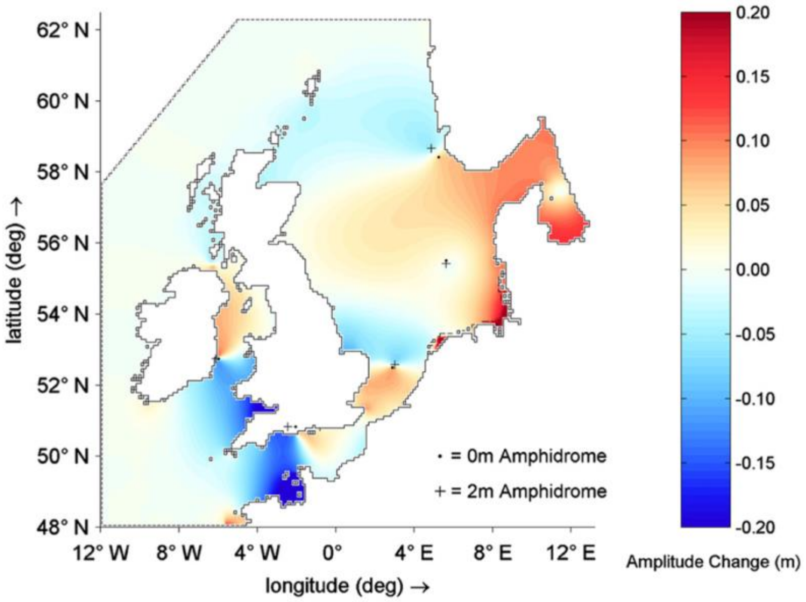


*Figure 31. Change in $M_2$ amplitude for a sea level rise of 2 m (Pickering et al., 2012)*

As can be seen in Figure 31, Pickering et al. (2012) find the same spatial pattern. They also find a decreasing $M_2$ amplitude at Dover and Immingham and they find the largest increase in amplitude at Delfzijl. The change in $M_2$ amplitude is in the same order as magnitude as the change found in this study, even though the sea level has risen much less than 2 m over the time period considered in this study (approximately 0.2 m between 1900 and 2014). That changes in $M_2$ amplitude are still comparable might be due to the non-linear response of $M_2$ to sea level rise (Pickering et al., 2012), or the boundaries of the model: it is assumed that the ocean tide did not change.

Figure 30 also shows the change in $M_4$ amplitude compared to sea level rise, but compared to the $M_2$ amplitude changes in $M_4$ amplitude are much more spatial variable. A relation between $M_4$ amplitude and sea level rise seems to be lacking. This might be due to the fact that the $M_4$ tide is generated in shallow water and is very much dependent on local geometry and bathymetry and these have changed over the past century for several locations. Variations in the $M_4$ amplitude at Vlissingen, for example, might be influenced more by the land reclamations than by sea level rise.

### 5.1.2. The effect of changes in $M_2$ and $M_4$ on tidal asymmetry and sediment transport

The tidal asymmetry is determined by the relation between the phases of $M_2$ and $M_4$:

$$\Delta\varphi = 2 \cdot \varphi_{M2} - \varphi_{M4}$$

If the phase difference is zero, there is no ebb or flood dominance. If the phase difference is positive, the tide is flood dominant and if it is negative, the tide is ebb dominant. The strength of the ebb or flood dominance, is determined by the ratio:

$$\frac{A_{M4}}{A_{M2}}$$

The larger this ratio, the stronger the ebb or flood dominance. How this ratio and the phase difference between $M_4$ and $M_2$ changed over time at Vlissingen is shown in Figure 32.

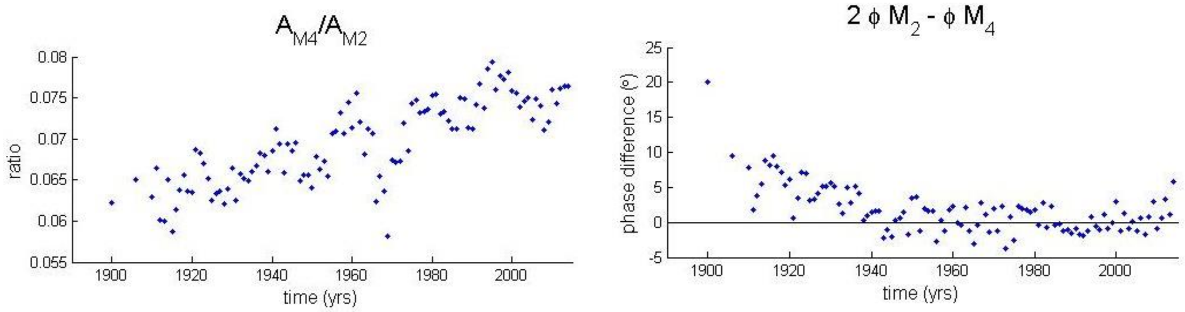


*Figure 32. Tidal asymmetry: amplitude $M_4$ over $M_2$ (left) and $2\varphi M_2 - \varphi M_4$ (right) at Vlissingen*

The tide has evolved from purely flood dominant, to fluctuating between ebb and flood dominant. This fluctuation is due to the 18.6-year cycle in the tide. The amplitude of the $M_4$ tide has increased relative to the $M_2$ tide. Table 4 shows the net sediment transport at Vlissingen, for different phase differences and ratio's $M_4/M_2$.

Table 4. Net import from the basin for different phase differences and ratio's $M_4/M_2$

| Δψ model input | Δψ Vlissingen | $Q_{bed}$ out of the basin **($10^{-1}$ $m^2/s$)** | $M_4/M_2$ model input | $M_4/M_2$ Vlissingen | $Q_{bed}$ out of the basin **($10^{-1}$ $m^2/s$)** |
|---|---|---|---|---|---|
| -90 | 10.1 | 0.28 | 0.00 | 0.01 | 1.18 |
| -70 | 5.3 | 0.62 | 0.05 | 0.04 | 1.07 |
| -51 | 0.7 | 0.98 | 0.10 | 0.08 | 0.98 |
| -30 | -4.5 | 1.41 | 0.15 | 0.12 | 0.92 |
| -10 | -9.5 | 1.83 | 0.20 | 0.20 | 0.86 |
| 10 | -14.6 | 2.23 | 0.25 | 0.20 | 0.86 |
| 30 | -19.7 | 2.61 | | | |
| 50 | -24.8 | 2.93 | | | |
| 70 | -29.9 | 3.20 | | | |
| 90 | -34.8 | 3.40 | | | |

As the phase difference at Vlissingen decreased from 20° in 1900 to 0° nowadays, the sediment transport from the basin towards the mouth will have increased. The increasing ratio $M_4/M_2$ could have led to a smaller sediment transport from the basin towards the mouth, but the increase in sediment transport due to the decreasing phase difference is larger.

Bolle et al. (2010) also studied the effects of a changing tidal asymmetry on sediment transport, but they found opposite results. This is due to a difference between the phase differences that are used in their study and in this study. The phase differences that were found in this study agree with the phase differences found by Kuijper and Lescinski (2012) . Improvements of harmonic analysis methods explain the difference between this study and Bolle et al. (2010).

The increase in sediment transport from the basin to the mouth, could result in a growth of the mouth area. However, Uit den Bogaard (1991) showed that the proximal part of the mouth area has been eroding. Possibly the mouth extended further into the sea, which is in agreement with the study of Haring (1955), who showed there was net deposition on the distal part of the mouth. The erosion of the mouth area, might also be attributed to clay. In the Delft3D model only sand was used, but clay responds differently to changes in tidal asymmetry, because of its smaller falling velocity.

The erosion of the mouth that Uit den Bogaard (1991) quantified is not well represented by the analysis of the historical maps in this study. No trend can be found in the absolute total cross-sectional area at the mouth. There might be too much noise due to the errors that are made during the digitization of the maps. The amount of measuring points and isobaths was not equal for all the maps and the average low water level was not stable over the past two centuries. Therefore it was chosen to show relative channel sizes (relative to the total channel area) in the rest of this study.

## 5.2. The effect of changes in the basin

Some drastic changes in the morphology of the basin near the mouth took place over the past two centuries. The Braakman and the Sloe have been reclaimed and the Honte shifted towards the north. This changed the flow direction from the basin to the mouth. In Figure 33 it is shown that these changes in the basin can be correlated to changes at the Wielingen in time.

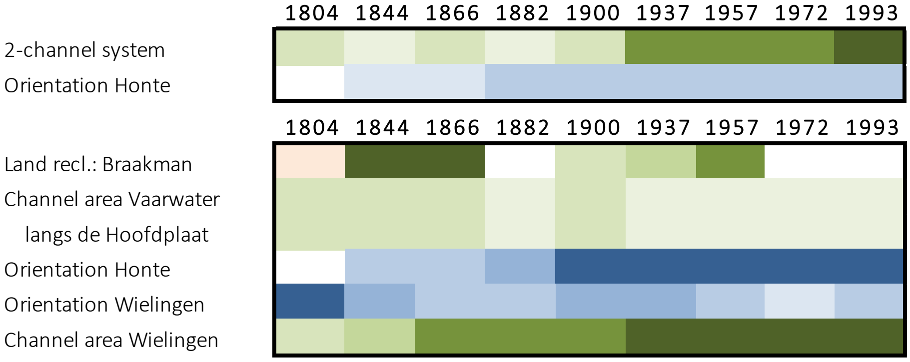


*Figure 33. Changes in the basin compared to changes in the mouth area*

Due to ongoing land reclamations the basin size of the Braakman decreased between 1800 and now. The Vaarwater langs de Hoofdplaat is the channel that supplied the Braakman and it has therefore decreased along with the basin area of the Braakman. This might have influenced the orientation of the Wielingen. As the Vaarwater langs de Hoofdplaat decreased, the flow towards the Wielingen from the northeast of the basin relatively increased. The Wielingen slightly changed its orientation towards the southwest.

This was enhanced by the changing orientation of the Honte. The orientation of the Honte changed, because its outer bend moved towards the north. This might have had different reasons:

- The channel became more north-south oriented in the east;
- Erosion of the shoal in front of the Sloe;
- Land reclamations and the building of dikes at the Sloe that forced the Honte in this position;
- The development of the 2-channel system, leading to a more sinusoidal shape of the ebb-channel.

The change in flow direction at the inlet might be related to the increase in channel area of the Wielingen. As the flow at the inlet became more directed towards the southwest, the Wielingen might have received a larger part of the tidal volumes. Ridderinkhof et al. (2013), however, have shown that the flow direction at the inlet does not affect the morphology of the mouth.

Despite the changes in the basin, the tidal prism did not change. Changes in tidal volumes through the channels in the mouth will therefore be solely due to a redistribution of ebb and flood volumes over the channels.

## 5.3. The effect of other human interventions

Several different kinds of human activities took place in and near the Western Scheldt over the past two centuries. The land reclamations have already been discussed in section 5.1, but there are also dikes built, the harbor of Zeebrugge was extended and the Eastern Scheldt has been closed off. The dredging and dumping activities are only of substantial magnitude since a few decades and can therefore not be related to changes in morphology in this study. The human interventions that can be linked to changes in the mouth area are the building of dikes and the extension of the harbor of Zeebrugge to the fusion of the Appelzak and the Wielingen (Figure 34) and the closure of the Eastern Scheldt to the deepening of the Oostgat in the west (Figure 35). The building of groynes could be related to the erosion of the proximal part of the mouth area over time, but the amount of sediment that is captured by the groynes is much smaller than the amount of sediment that has been eroded from the mouth area.

*Figure 34. Human interventions compared to the fusion of the Appelzak and the Wielingen*

Although the cross-sectional area of the Appelzak did not decrease, the Appelzak is disappearing as it is fusing with the Wielingen. The Paardenmarkt, the shoal between the Wielingen and the Appelzak, is lowering and the depth of the Appelzak is decreasing. In time this can be related to the building of dikes at Zeeuwsch-Vlaanderen, but a physical explanation for a relation between those two is lacking. The extension of the harbor of Zeebrugge into the sea could have influenced the flow through the Appelzak, but this happened much later than the start of the fusion of the Wielingen and the Appelzak. A third explanation for the fusion of the Appelzak and the Wielingen is the widening of the Wielingen. In section 5.4 this widening will be further discussed.

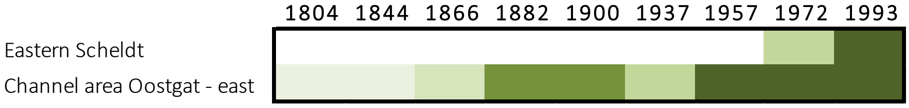


*Figure 35. The closure of the Eastern Scheldt and the deepening of the Oostgat*

The Oostgat is relatively stable. In the east the Oostgat gradually grew a bit, mainly due to a deepening of the channel. In the West the Oostgat was stable until 1957, but then the cross-sectional area had suddenly doubled by 1972. This coincides with the construction of some back-barrier dams in the Eastern Scheldt, which resulted in an increase in tidal prism in the Eastern Scheldt (Figure 36). This increase in tidal prism, might have increased the flow velocities in the western part of the Oostgat, resulting in a deepening there. So although the deepening of the Oostgat cannot be related to the closure of the Eastern Scheldt (1986), it can be related to other changes in the Eastern Scheldt.

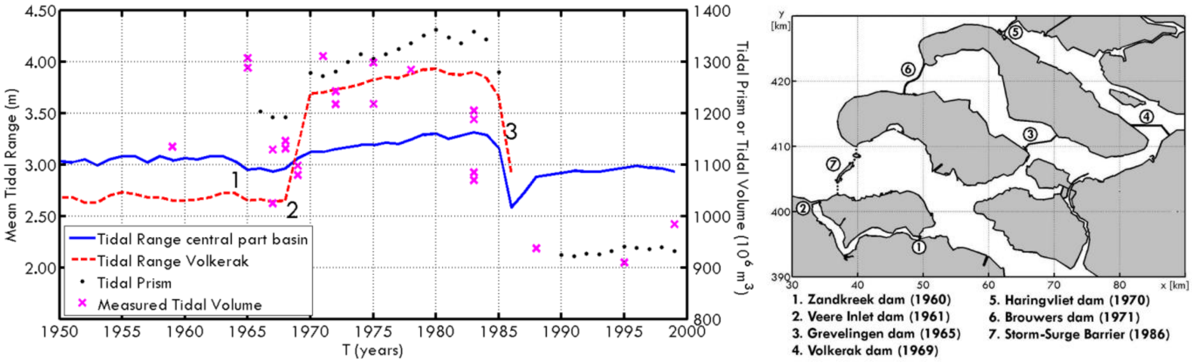


*Figure 36. Tidal prism and measured tidal volume of the Eastern Scheldt and mean tidal range inside the Keeten and Volkerak channels (De Bok, 2001). Numbers indicate finalization of dams: (1) Grevelingen dam. (2) Volkerak dam. (3) Storm surge barrier (Eelkema, 2013)*

## 5.4. The effect of morphological changes in the mouth

In this chapter multiple external driving mechanisms behind the changes in the mouth have been discussed. However, morphological changes in the mouth could also trigger other changes themselves. Figure 37 shows the morphological changes in the mouth that can be related in time.

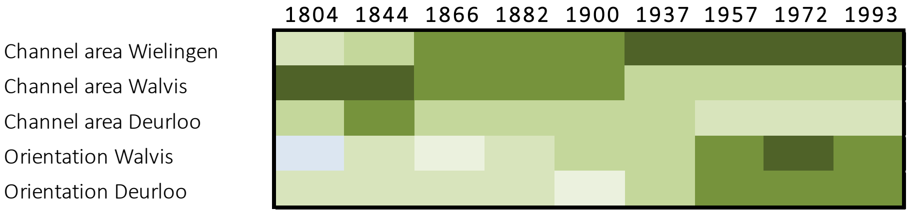


*Figure 37. Morphological changes in the mouth over time*

One of the most significant changes in the mouth is the enlargement of the Wielingen. This is mainly due to a widening of the channel. That the Wielingen did widen instead of deepen might be due to the presence of stiff clay layers in the subsurface in the east of the Wielingen (Figure 3). The growth of the Wielingen can be explained by the preferred location of the main ebb channel according to van den Berg (1987) in combination with the delaying effect of the geology (van den Berg, 1987; see also section 0).

As the Wielingen became larger, the Scheur and the Deurloo became proportionally smaller, because of a redistribution of the tidal volume. With the decreasing tidal volume through the Deurloo and the Scheur, the east-west flow decreased, leading to a relative importance of the North Sea tide. This has resulted in a change in orientation of the Deurloo towards the north and the emergence of the Channel of the Walvis. When the Channel of the Walvis broke through, it pushed the Deurloo even further to the north. Meanwhile the Scheur has almost entirely disappeared.

# 6. Conclusion

In the basin, the major changes that took place over the past two centuries are the reclamation of land and the development of the two-channel system. The land reclamations at the Braakman have led to a significant decrease in the cross-sectional area of the Vaarwater langs de Hoofdgeul. Together with the changing orientation of the Honte, this led to a change in the flow direction at the inlet. The changing orientation of the Honte might have had different reasons: 1) Land reclamations at the Sloe, 2) the erosion of shoals, or 3) the development of the two-channel system.

The Wielingen has significantly enlarged over the past two centuries. This might be due to the change in flow direction at the inlet. As the flow direction at the inlet shifted towards the southwest, the southern channel, the Wielingen, might have become more favored compared to the northern channels, the Deurloo and the Scheur. The enlargement of the Wielingen might also be due to the preferred location of the main ebb channel and the delaying effect of geology.

The enlargement of the Wielingen is mainly due to a widening of the channel, because of the presence of stiff clay layers in the subsoil. Because of this widening the Paardenmarkt is eroding and the Wielingen has started fusing with the Appelzak.

As the Wielingen increased, the Scheur and the Deurloo started receiving smaller parts of the tidal volume. As a result, these channels became smaller and the North Sea tide became relatively important and they shifted towards the North. Eventually the Channel of the Walvis developed, most likely taking over the Scheurs function, but with a more northwestern direction. As the Channel of the Walvis broke through in the north, it pushed the Deurloo further towards the north.

The Oostgat has been relatively stable over the past two centuries as it is fixed by dikes in the north. The only change that took place was the deepening of the western part in the 1960's. This deepening was likely due to the building of back-barrier dams in the Eastern Scheldt, which resulted in an increase in tidal volume for the Eastern Scheldt. Apart from the land reclamations and the changes in the Eastern Scheldt there are no human interventions that are found to be related to changes in the morphology of the mouth. Most of them because they probably did not have large effects on the mouth. The dredging and dumping activities because they started too recently.

The tidal prism was constant over the past two centuries, judging from the stable inlet area. The tidal asymmetry, on the other hand, did change. The $M_2$ amplitude changed because of sea level rise. The $M_4$ amplitude and phase also changed, but this is more likely due to changes in the geometry of the basin. As the $M_2$ and $M_4$ tides changed, the tide at Vlissingen became less flood dominant. This resulted in a larger export of sand from the basin. This is not in agreement with the observed erosion of the mouth area, but this might be attributed to the different behavior of clay. All the conclusions are summarized in Figure 38.

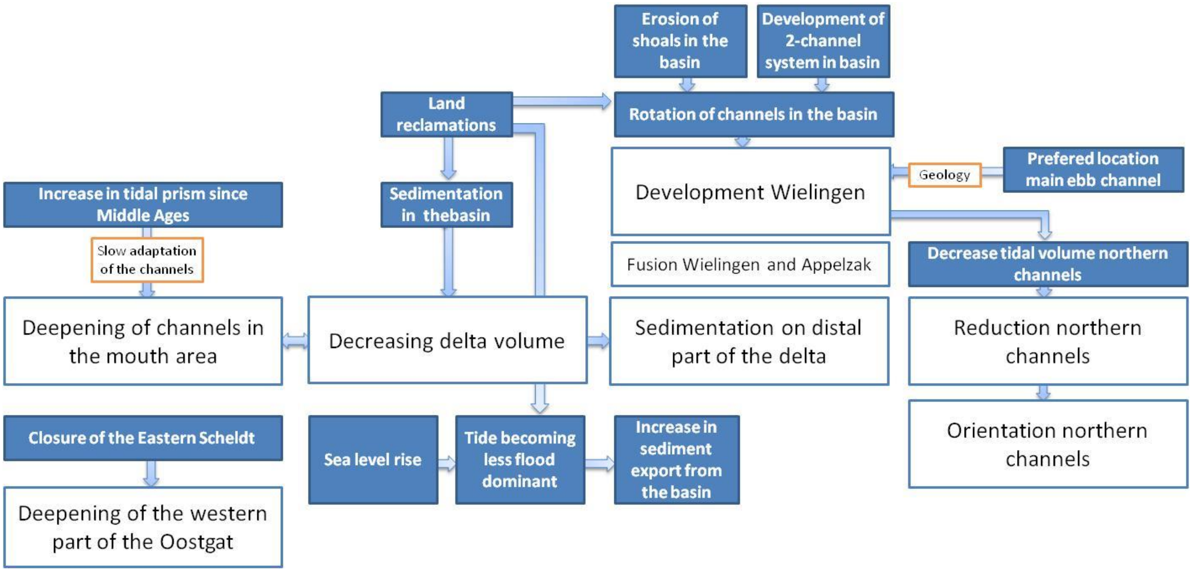


*Figure 38. Driving mechanisms and morphological changes*

# References

Allersma, E., 1994. *Geulen in estuaria, 1-D modellering van evenwijdige geulen.* Rapportnummer H1828, WL|Delft Hydraulics, Delft. I.o.v. Rijkswaterstaat, Directie Zeeland en Dienst getijdewateren

Van den Berg, J.H., 1987. *Toelichting bij de isallobatenkaart Voordelta 1975-1984.* Middelburg: Rijkswaterstaat Report, ZL 87.0020

Van den Berg, J.H., Jeuken, M.C.J.L., van der Spek, A.J.F., 1996. *Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary*. In: Nordstrom, K.F., Roman, C.T., 1996. Estuarine Shores: evolution, environment and human alterations. John Wiley & sons, Chichester, pp. 155-184

Bolle, A., Wang, Z.B., Amos, C., de Ronde, J., 2010. *The influence of changes in tidal asymmetry on residual sediment transport in the Western Scheldt.* Cont. Shelf Res. 30, pp. 871-882

British oceanographic data centre. Downloaded: October, 2015, from: http://www.bodc.ac.uk/data/

Codiga, D.L., 2011. *Unified Tidal Analysis and Prediction Using the U Tide Matlab Functions*. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 59pp.

Coen, I., 1988. *Ontstaan en ontwikkeling van de Westerschelde*. Water, 7 (43/1), pp. 156-162

Damen, J., 2014. *Coastal erosion processes in tidal channel Oostgat.* Universiteit Twente: MsC Thesis

van Eck, G.Th.M., 1999. *De ScheldeAtlas, een beeld van een estuarium*. Rijksinstituut voor Kust en Zee/Schelde informatiecentrum: Middelburg, 120pp.

Eelkema, M., 2013. *Eastern Scheldt Inlet Morphodynamics.* PhD thesis, TU Delft

Elias, E., van der Spek, A., 2015. *Uitwerking sedimentbudget van de Westerscheldemonding – concept.* Deltares

Van Enckevort, I., 1996a. *Morfologisch onderzoek Westerschelde monding, deel 1 – Inventarisatie beschikbare literatuur over en metingen in de Westerschelde monding*. IMAU, Utrecht University.

Van Enckevort, I., 1996b. *Morfologisch onderzoek Westerschelde monding, deel 2 – Morfologische ontwikkeling van de Westerschelde monding sinds 1800.* IMAU, Utrecht University.

Du Four, I., Schelfaut, K., Van Heteren, S., Van Dijk, T., Van Lancker, V., 2006. *Geologie en sedimentologie van het Westerscheldemondingsgebied. Coosen J., Mees J., Seys J. en Fockedey N.(Eds.). Studiedag: De Vlakte van de Raan van onder het stof gehaald. Oostende* 13.

Haring, J., 1955. *Zandbalansen van de zuidwestelijke wateren van Nederland over de perioden 1872-1933 en 1933-1952.* Rijkswaterstaat rapport nr. 3.

Janssens, J., Verwaest, T., Mostaert, F., 2012. *Morfologische evolutie van het Belgisch continentaal plat gedurende de laatste 150 jaar.* Deelrapport in het kader van het Quest4D-project. Versie 2_0. WL Rapporten, 814_02. Waterbouwkundig Laboratorium: Antwerpen, België

Jeuken, M.C.J.L., 2000. *On morphological behaviour of tidal channels in the Westerschelde estuary.* Phd. Thesis Universiteit Utrecht

Kuijper, K., Lescinski, J., 2012. *Data Analyses water levels ebb and flood volumes and bathymetries Western Scheldt.* IMDC nv i.s.m. Deltares, Svašek and Arcadis Nederland, basisrapport grootschalige ontwikkeling G-5, 190 pp.

Kuijper, K., 2013. *Aanvullend onderzoek historische ontwikkeling getij in het Schelde-estuarium – Data-analyse en toepassingen analytisch model.* IMDC nv i.s.m. Deltares, Svašek and Arcadis Nederland, basisrapport grootschalige ontwikkeling G-8, 109 pp.

Liek, G.J. *Baggeren en storten in de Westerschelde*. Downloaded: June 2013, from: http://www.watlab.be/nl/actueel/agenda_oud/bestanden/studiedagwalsoorden/baggeren%20en%20storten%20in%20de%20westerschelde

De Looff, D., Verhagen, J.H., 1986. *Mondingsgebied van de Westerschelde: getijstrolingen, golfklimaatgegevens, bodemligging en morfologische processen.* Rijkswaterstaat, rapport GWWS-86, 404, in: Van Enckevort, I., 1996. *Morfologisch onderzoek Westerschelde monding, deel 2 – Morfologische ontwikkeling van de Westerschelde monding sinds 1800.* IMAU, Utrecht University.

Van Oyen, T., Van der Vegt, M., De Maerschalk, B., Nnafie, A., Verwaest, T., Mostaert, F., 2015. *Verbetering Modelinstrumentarium Lange termijn Morfologie – Subreport 1 – Literature Review: morphology of the Scheldt estuary mouth.* Flanders Hydraulics Research

Parée, E., 2002. *De toestand van de bodem van de Westerschelde aan het begin van de verruiming 48'/43'.* Herziene TO voor de bodem van de Westerschelde, Rijkswaterstaat

Pickering, M.D., Wells, N.C., Horsburgh, K.J., Green, J.A.M., 2012. *The Impact of future sea-level rise on the European Shelf tides.* Cont. Shelf Res. 35, p. 1-15

Plancke, Y., Vereecken, H., Claeys, S., Verwaest, T., Mostaert, F., 2014. *Hydro- en sedimentdynamica in het mondingsgebied van het Schelde-estuarium: Deelrapport 1 – Factual data rapport frame- en puntmetingen periode augustus 2014.* Antwerpen: Waterbouwkundig Laboratorium

Ridderinkhof, W., de Swart, H.E., van der Vegt, M., Hoekstra, P., 2013. *Influence of the back-barrier basin length on the geometry of ebb-tidal deltas.* Ocean Dynamics 64, pp. 1333-1348

Van der Slikke, 1997. *Grootschalige zandbalans van de Westerscheldemonding (1969-1993). Een inventarisatie van dieptegegevens (1800-1996).* IMAU, Utrecht University

Van der Spek, A.J.F., 1997. *Tidal asymmetry and long-term evolution of Holocene tidal basins in the Netherlands: simulation of paelo-tides in the Schelde estuary.* Marine Geology 141, pp. 71-90

Svašek, 1994. *Verklarend onderzoek drempels Westerschelde – deel 1: Tekst en tabellen.* Proj. Nr. 940

Terwindt, J.H., 1967. *MUD transport in the Dutch delta area and along the adjacent coastline.* Netherlands Journal of Sea Res., 505-531

Trouw, K., Zimmermann, N., Wang, L.., De Maerschalck, B., Delgado, R., Verwaest, T., Mostaert, F., 2015. *Scientific support regarding hydrodynamics and sand transport in the coastal zone: Literature and data review coastal zone Zeebrugge - Zwin*. Version 4_0. WL Rapporten, 12_107. Flanders Hydraulics Research. Antwerp, Belgium.

Uit den Bogaard, LA., 1991. *Relatie zandbalans Westerschelde met de morfologie van de ebgetijde delta en kust.* Instituut voor Ruimtelijk Onderzoek, Universiteit Utrecht, Rapport GEOPRO 1991.021.

Van Veen, J., 1950. *Eb- en Vloedschaar systemen in de Nederlandse Getijwateren.* Tijdschrift Koninklijk Nederlandsch Aardrijkskundig Genootschap, 67, pp. 303-325

Verhagen, H.J., van Rossum, H. (1989). *Kustverdediging na 1990, Technisch Rapport 12: Strandhoofden en paalrijen: evaluatie van hun werking*. Min V&W, Rijkswaterstaat, Dienst Weg- en Waterbouwkunde, ’s-Gravenhage.

Vroon, J., Storm, C., Coosen, J., 1997. *Westerschelde, stram of struis? – eindrapport van het project Oostwest, een studie naar de beïnvloeding van fysieke en verwante biologische patronen in een estuarium.* Rapport RIKZ-97.023

Wahl, T., Haigh, I.D., Woodworth, P.L., Albrecht, F., Dillingh, D., Jensen, J., Nicholls, R.J., Weisse, R., Wöppelmann, G., 2013. *Observed mean sea level changes around the North Sea coastline from 1800 to present.* Earth-Science Reviews, 24, p. 51-67

Waterbase. Downloaded: October 2015, from: http://live.waterbase.nl/

Woodworth, P.L., 2010. *A survey of recent changes in the main components of the ocean tide.* Cont. Shelf Res. 30, pp. 1680-1691

# Appendix 1 – List of maps

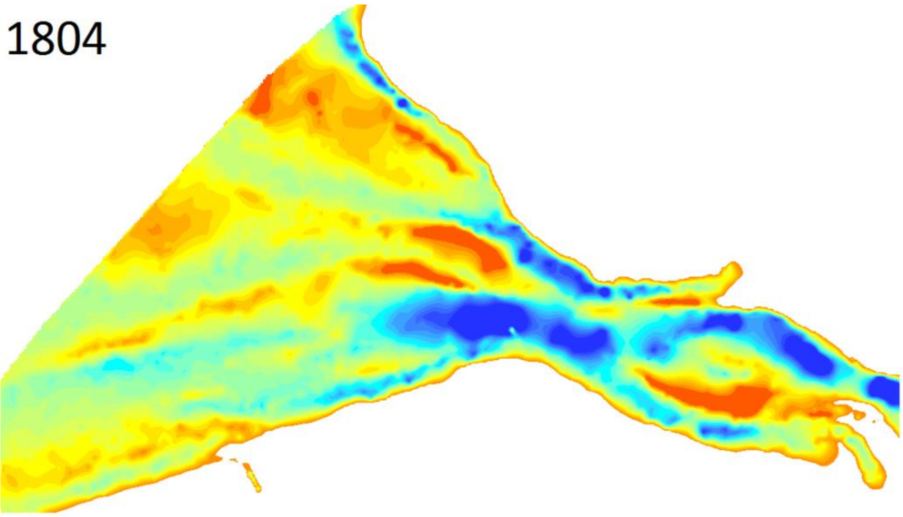
| Year | Mouth/ basin? | Scale | Depth relative to ** | Source | Name | Maker |
|---|---|---|---|---|---|---|
| **1817*** | MB | ? | g.l.l.w.s.eq *** | Waterbouwkundig Laboratorium | Carte réduite des côtes des Pays-Bas (depuis Ostende jusqu'a Hellevoetsluis | Beautemps-Beaupré |
| **1844** | M | 1:50.000 | g.l.w.d. | Nationaal Archief Den Haag | Hydrografische kaart der zeegaten van de Monden der Schelde met de Reeden van Vlissingen en Veere | M.J.C. van der Hoop |
| **1866** | M | 1:100.000 | g.l.w. | Archive MDK | Carte Générale des bancs de Flandres - compris entre Gravelines et l'Embouchure de l'Escaut | Mr Stessels, lientenant de vaisseau de 1re classe |
| **1867** | B | 1:25.000 | | FelixArchief | Hydrographische kaart der Honte of Westerschelde - van bewesten Vlissingen tot boven Den Doel | Departement van Marine (NL) |
| **1880** | B | 1:60.000 | | FelixArchief | Escaut. Depuis Flessingue jusqu'a Burght | |
| **1884** | M | 1:40.000 | g.l.w. | FelixArchief | Embouchure de l'Escaut - Partie comprise entre Flessingue et "Spanjaard Duin" | |
| **1899** | B | 1:20.000 | | FelixArchief/Waterbouwkundig Laboratorium | Carte hydrographique de l'Escaut Néerlandais | Ministerie van Financien (BE) |
| **1900** | M | 1:40.000 | g.l.w. | FelixArchief | Embouchure de l'Escaut | Ministerie van Financien (BE) |
| **1938** | B | 1:50.000 | g.l.w.s. | FelixArchief | Hydrografie Schelde - Vlissingen-Antwerpen | Antwerpse Zeediensten |
| **1938** | M | 1:100.000 | g.l.w.s. | Archive MDK | Hydrografie Noordzee - Vlaamse Banken | Ministerie van transport |
| **1953** | B | 1:50.000 | | FelixArchief | Hydrografie Schelde - Vlissingen-Antwerpen | Antwerpse Zeediensten |
| **1959 - 1969** | M | 1:100.000 | g.l.w.s. | Archive MDK | Noordzee - Vlaamse Banken | Hydrografische dienst der kust |
| **1972** | B | 1:50.000 | | FelixArchief | Westerschelde - Vlissingen-Antwerpen | Samengesteld uit Belgische en Nederlandse opnemingen |
| **1972** | M | 1:50.000 | g.l.w.s. | Waterbouwkundig Laboratorium | Noordzee - Belgisch-Nederlandse kust - monding der Westerschelde - van Oostende tot Westkapelle | Hydrografische dienst der kust |
| **1991** | M | 1:100.000 | | VLIZ - wetenschatten | Noordzee - Vlaamse Banken | Dienst der kusthavens - hydrografie |
| **1996** | B | 1:50.000 | | FelixArchief | Westerschelde - Vlissingen-Antwerpen | Composition of diff. measurements |

* Measurements from 1804

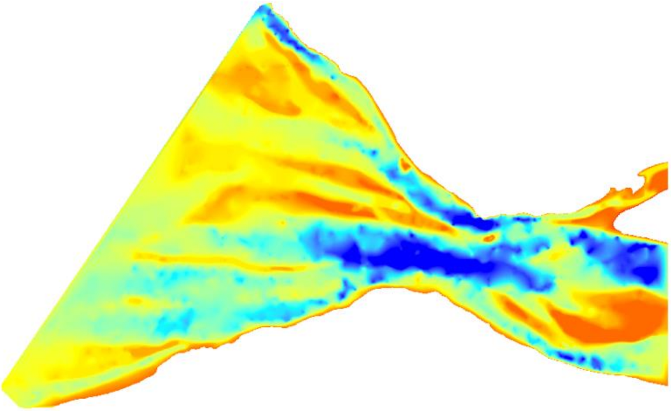
** All depths are converted to depths relative to average low water (g.l.w.). G.l.w.d.: average low water at neap tide (+ 3 dm relative to g.l.w.); g.l.w.s.: average low water at spring tide (-4 dm relative to g.l.w.); g.l.l.w.eq.: average low water at equinoxe tide (-8 dm relative to g.l.w.)

* ** Depth in pied de France; 1 pied de France = 35 cm

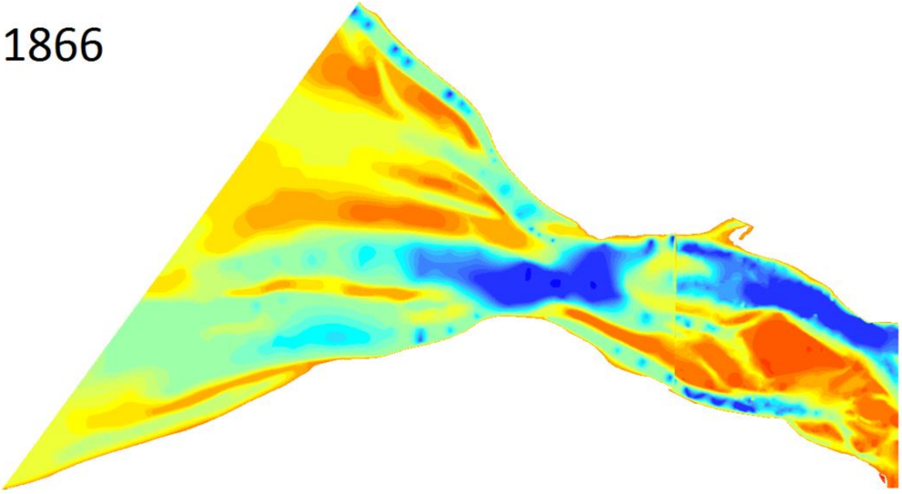
## Appendix 2 – Digitized maps



1804

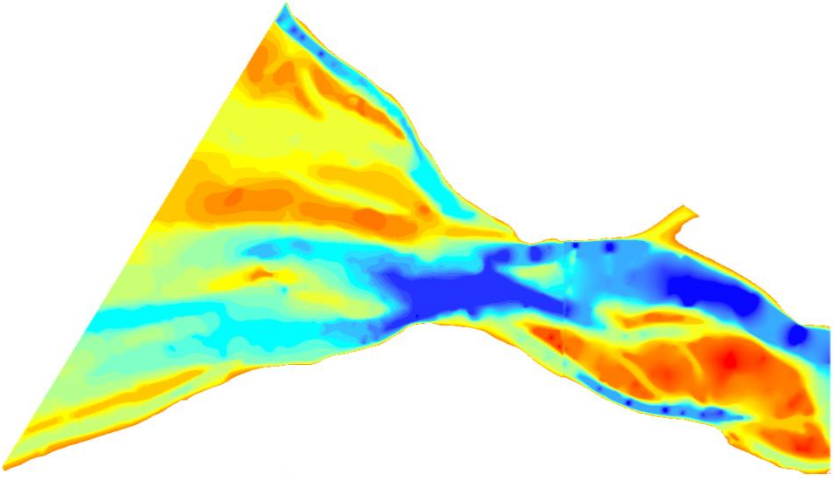


1844

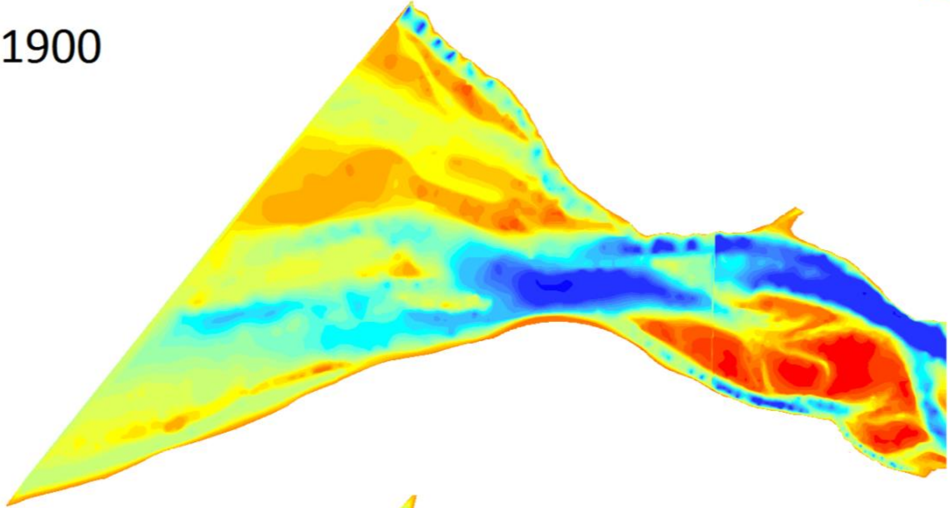


1866

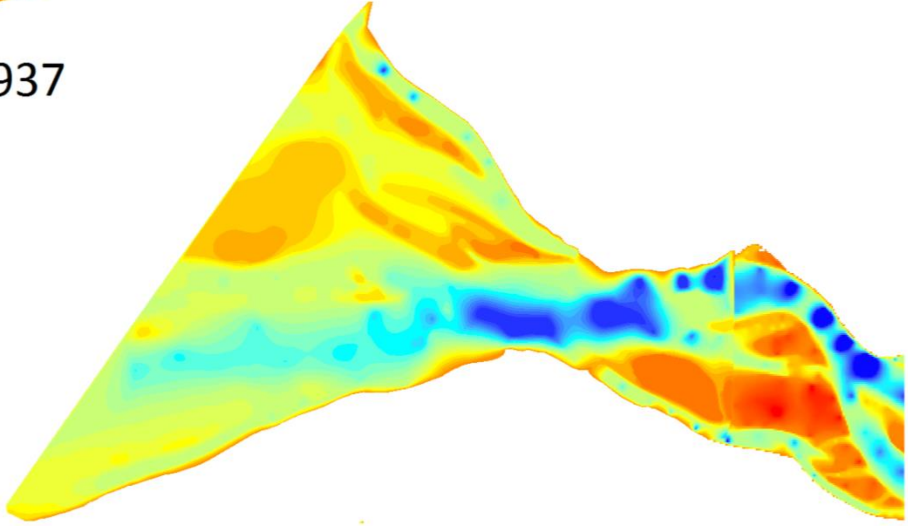
1882

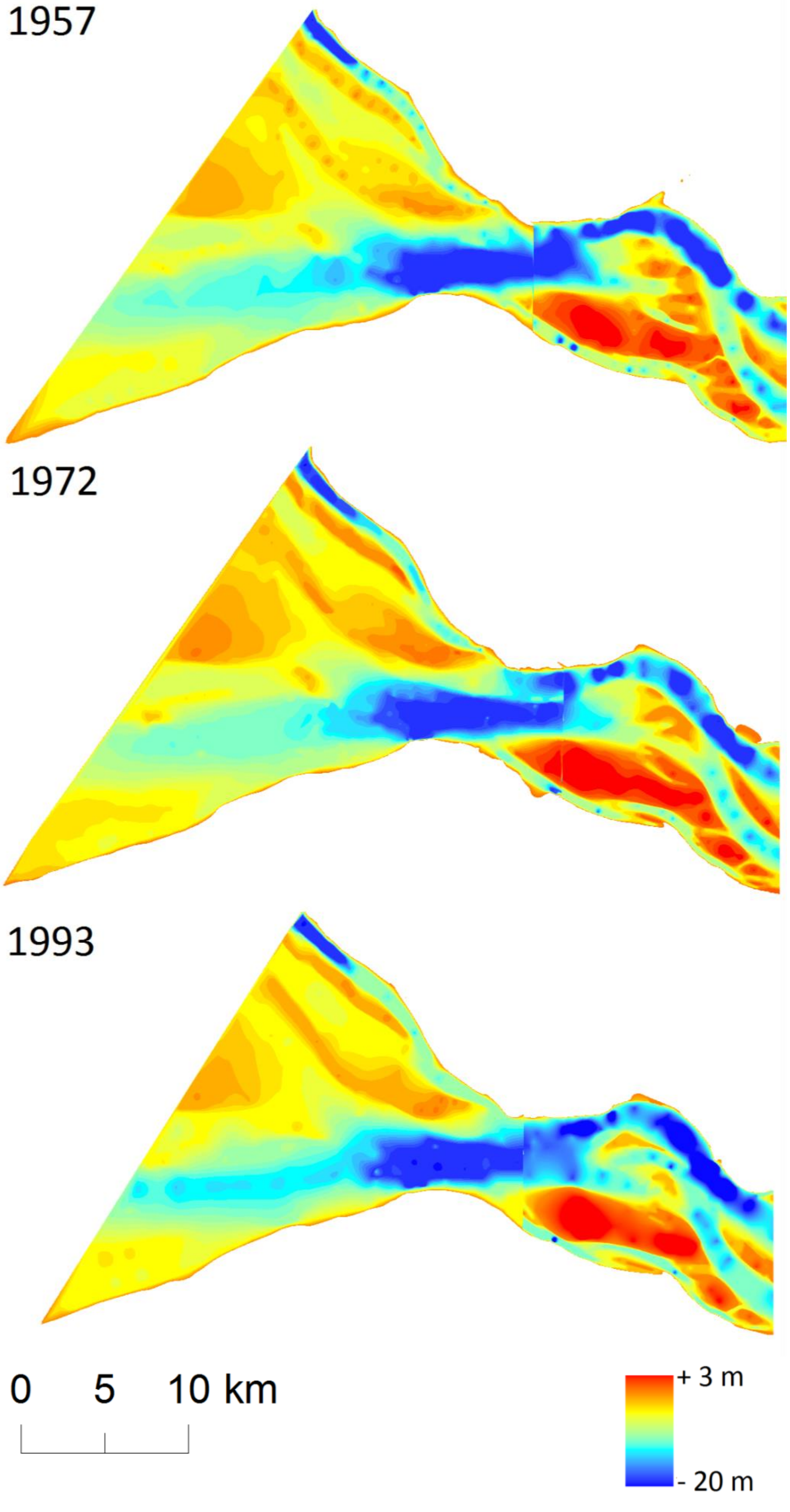


1900



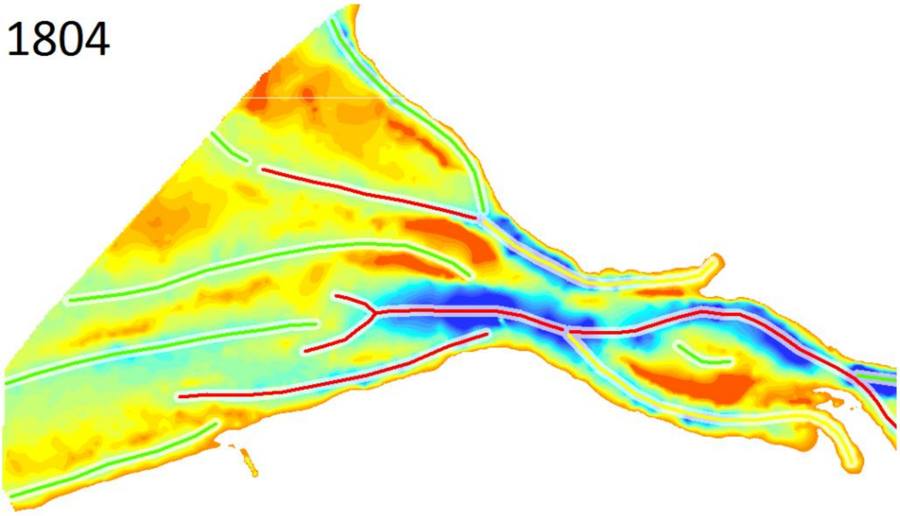
1937



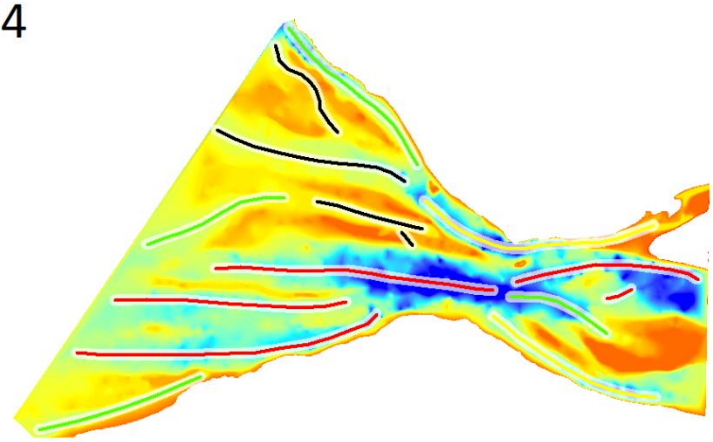

1957
1972
1993
0
5
10 km
+ 3 m
- 20 m

## Appendix 3 – Digitized maps with channel identification

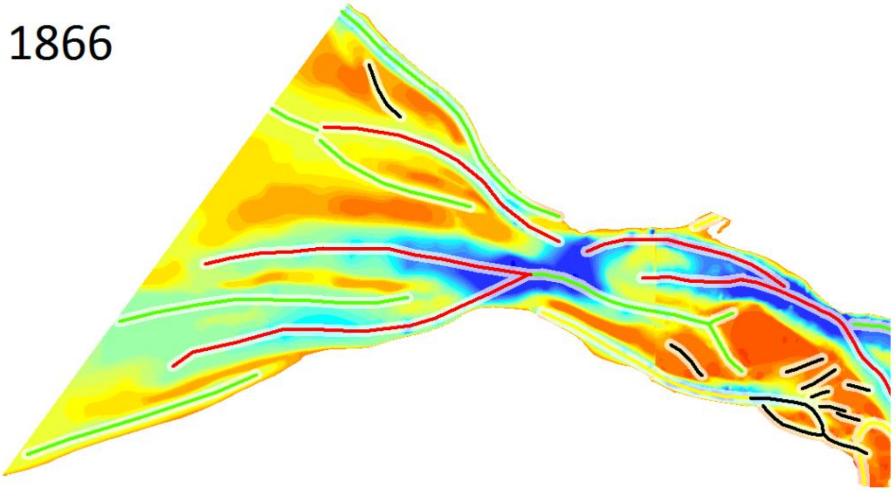
1804



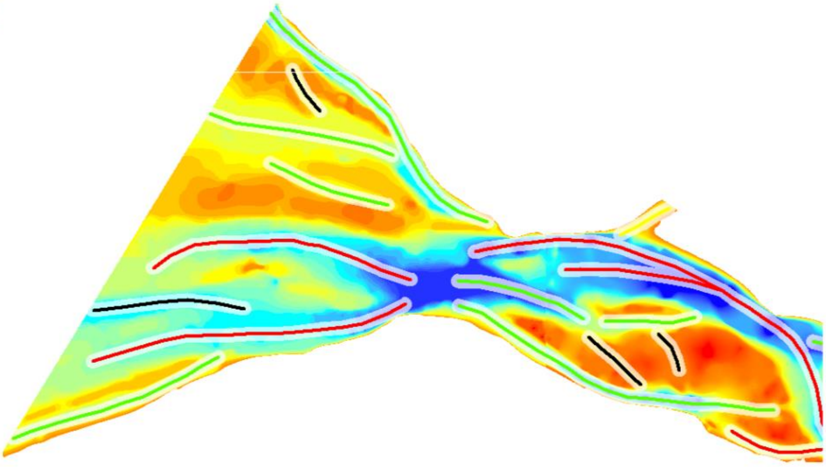
1844



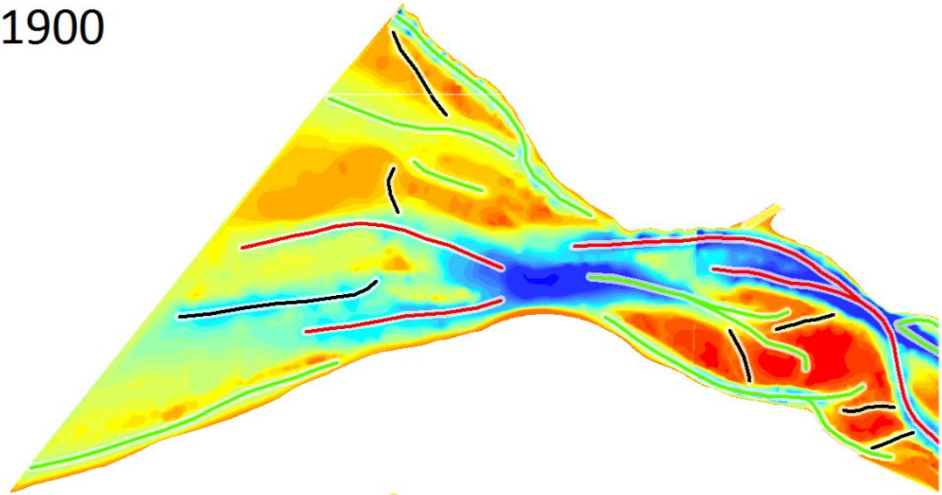
1866



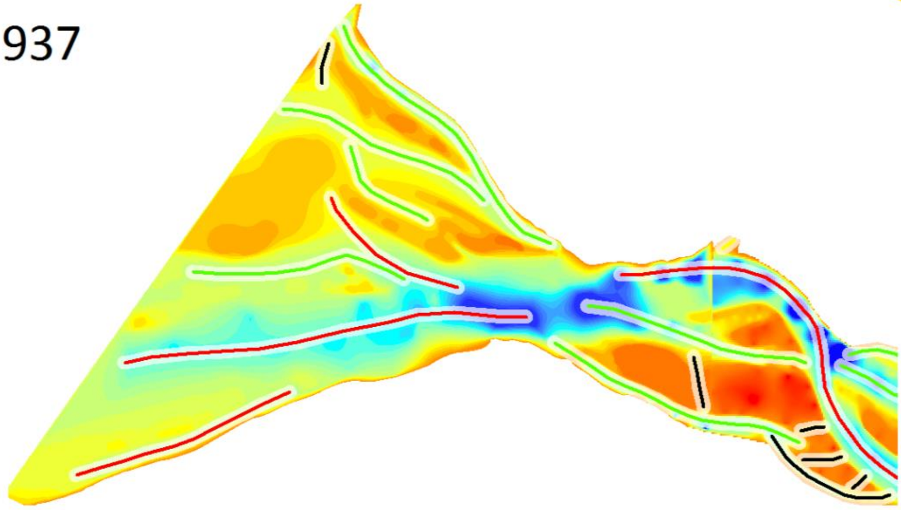
1882

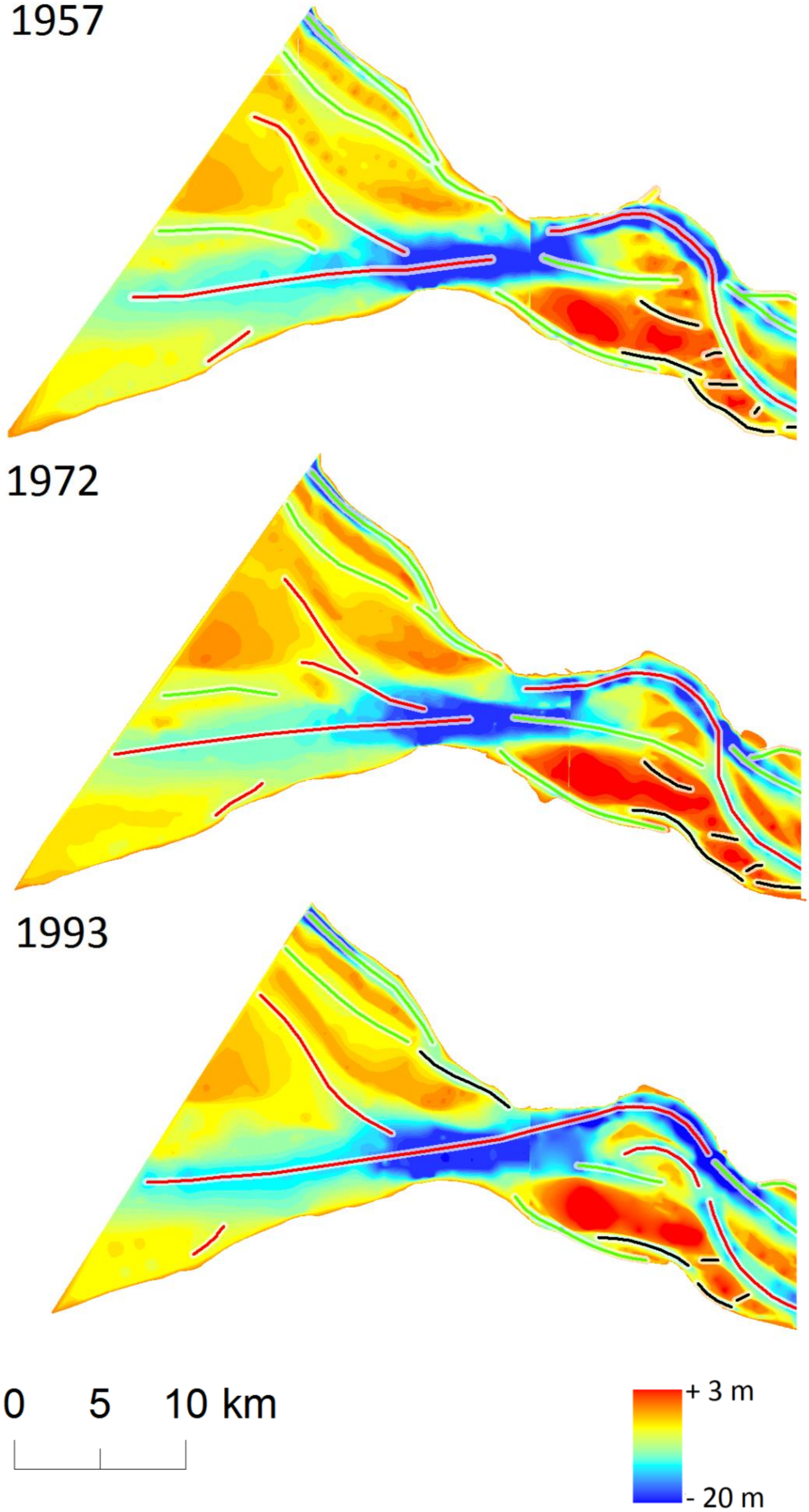


1900

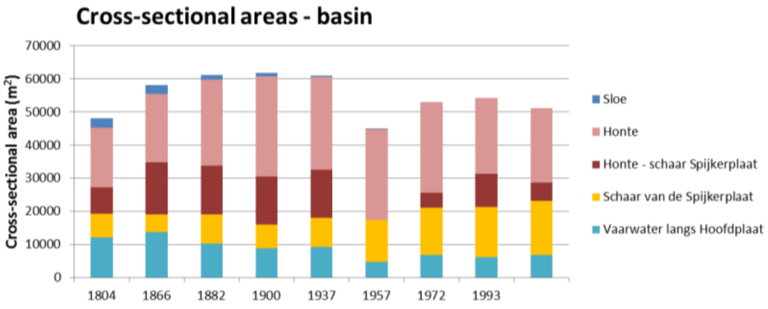


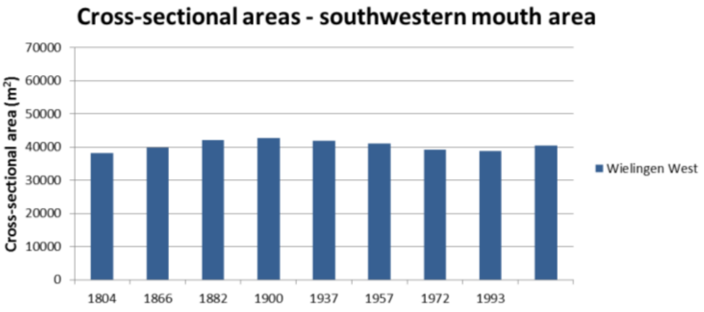
1937

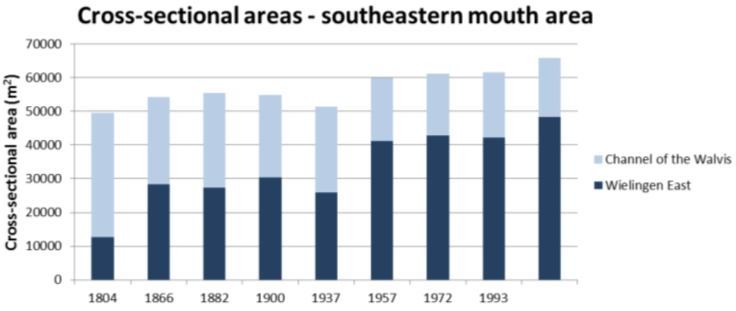


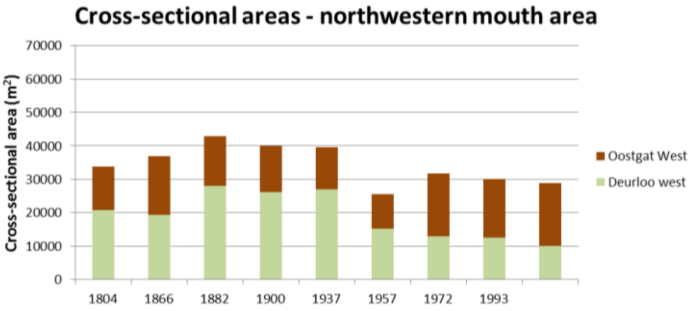

1957
1972
1993
0
5
10 km
+ 3 m
- 20 m

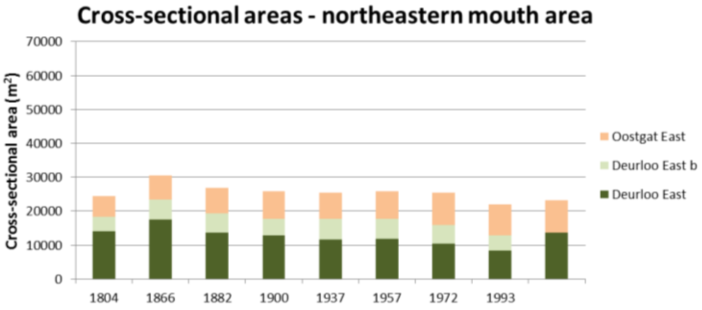
# Appendix 4 – Absolute cross-sectional areas





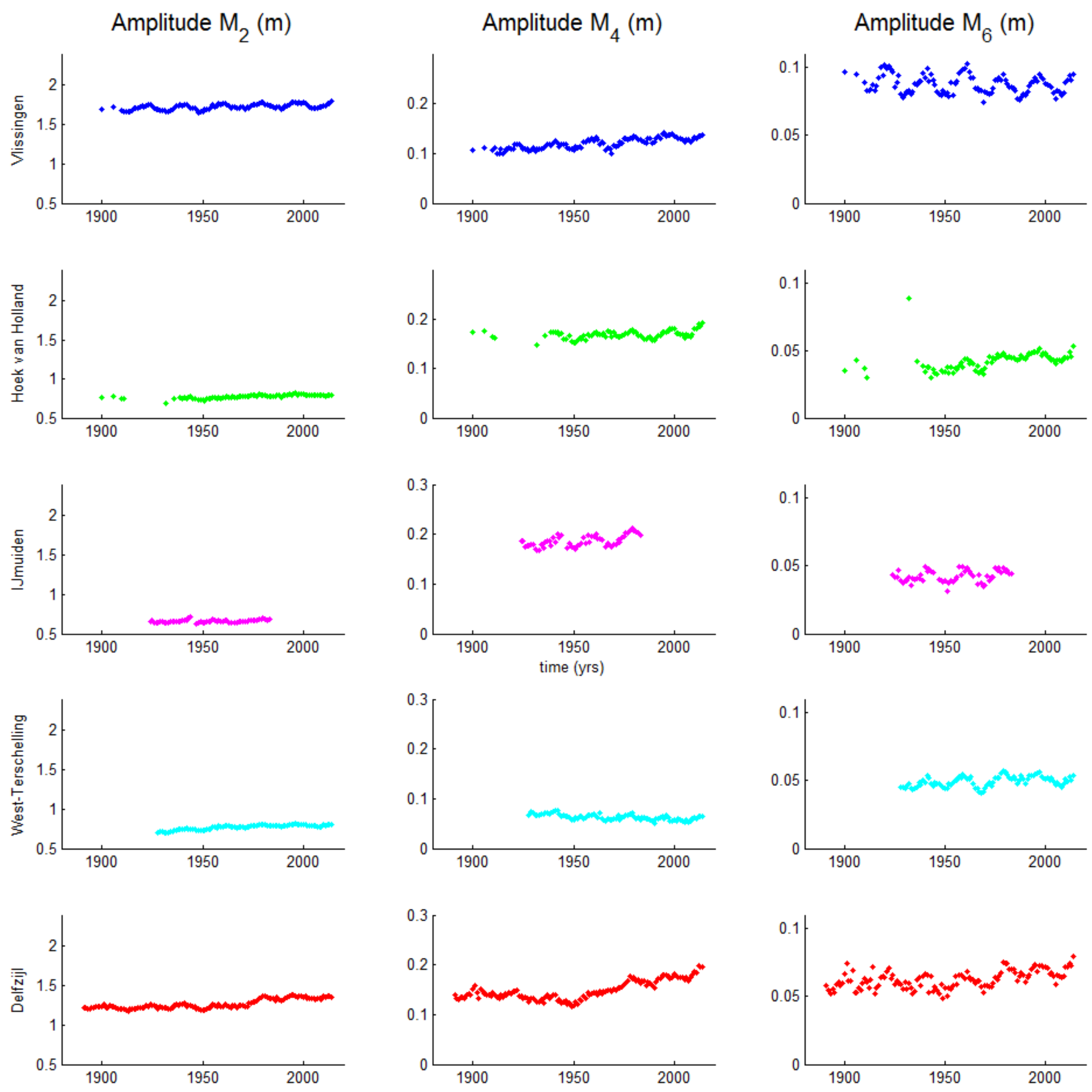




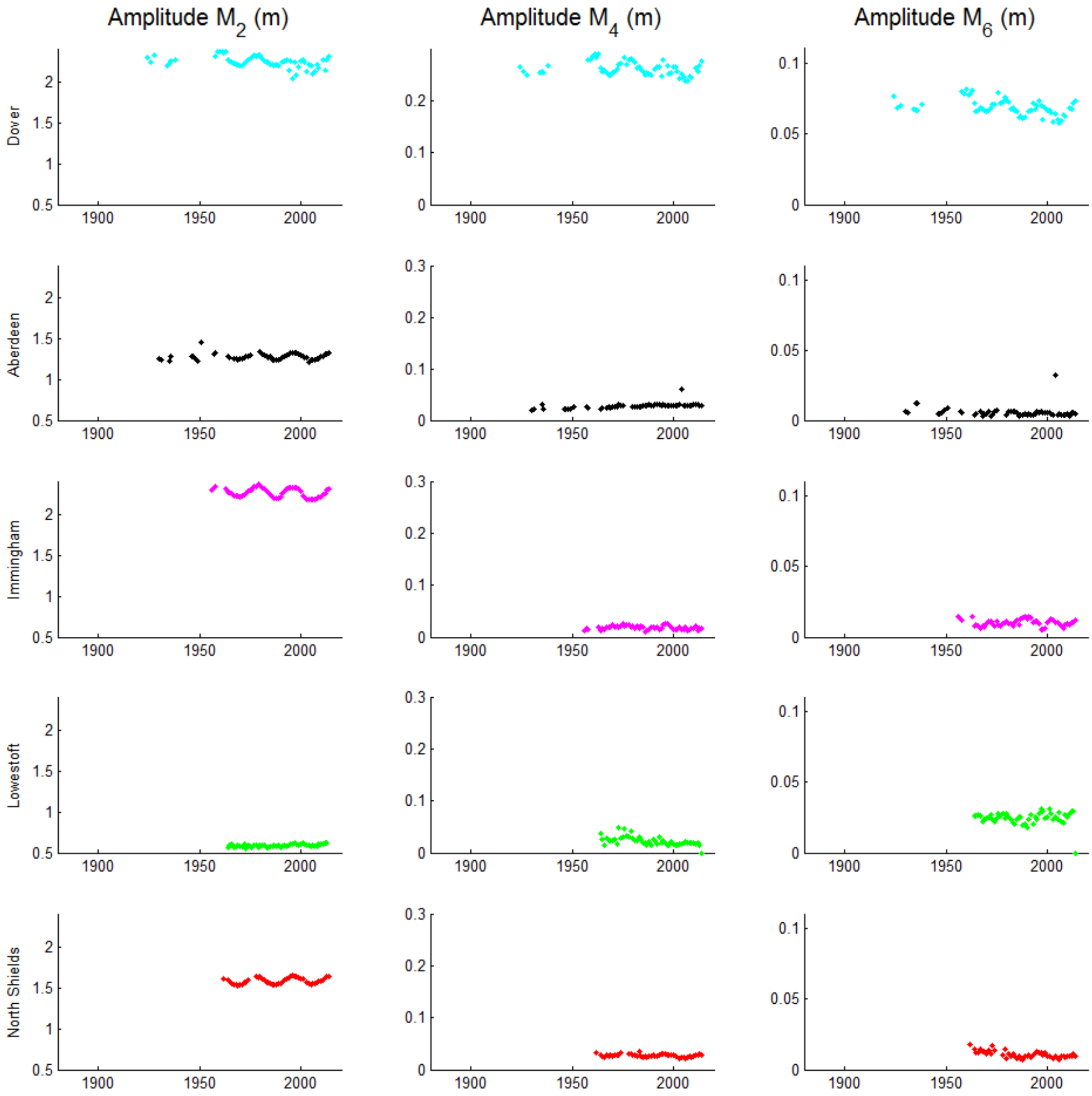


# Appendix 5 – time series of tidal characteristics

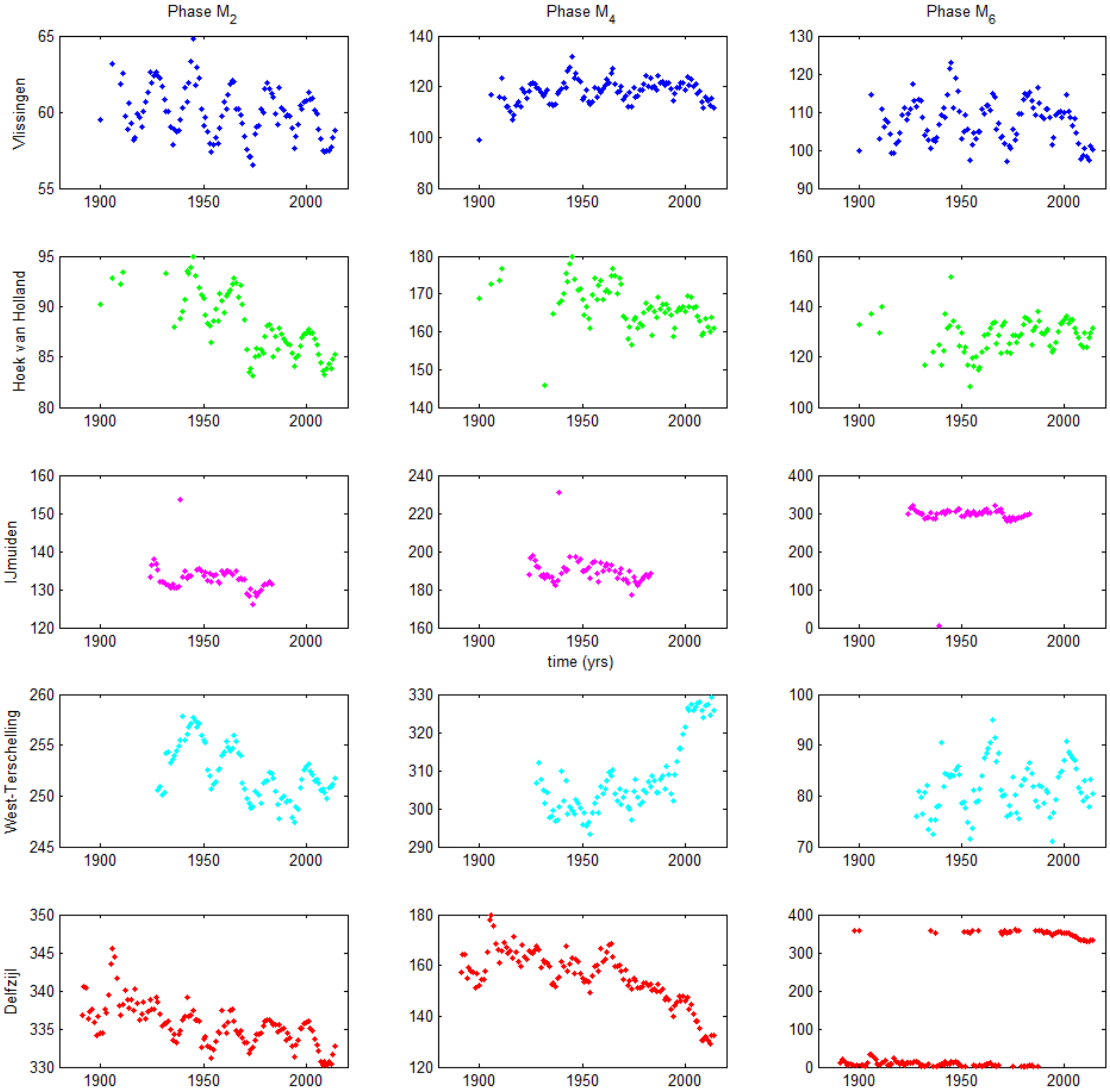
## Amplitudes Dutch stations



# Amplitudes English stations



# Phases Dutch stations



# Phases English stations