TIDAL DIVIDES

A STUDY ON A SIMPLIFIED CASE AND THE DUTCH WADDEN SEA

MSc. thesis of Julia Vroom

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Preface

This thesis marks the end of my study Civil Engineering at Delft University of Technology. After considering multiple graduation projects, I decided to graduate at Witteveen+Bos in Rotterdam. This company just started a study on the effects of deepening of a shipping lane in the Wadden Sea on hydrodynamics and morphology. This channel is called the 'Boontjes'. For my graduation project, I decided to focus on the large-scale and long-term processes in the Wadden Sea. After reading some literature, I found out that not much is known on tidal divides in the Wadden Sea, especially the doubt about the existence of a tidal divide between Marsdiep and Vlie (near the Boontjes) had my interest from the start. This resulted in a research on tidal divides, as you will read in this thesis.

I would like to thank everybody who helped me during graduation. Marcel Stive, Zheng Wang, Robert-Jan Labeur and Bram van Prooijen, thanks for your input and enthusiasm! Special thanks to Maarten Jansen, who supported me on daily basis, always took the time to discuss the latest results and gave me the opportunity to graduate at Witteveen+Bos. This was a very pleasant stay and I would like to thank everybody from the office as well. Last but not least I would like to thank Martijn, just for everything.

Julia Vroom
Rotterdam, June 2011

Summary

The Wadden Sea is an important area for nature and mankind. It is a vital region for animal species and bird migration, but is also used for recreation, gas extraction and sand, salt and shell mining. Human interventions and increasing relative sea level rise disturb the dynamic equilibrium of this unique system. To be able to manage this system in a thoughtful manner, the physics behind this system has to be understood. The equilibrium state of the basins is of interest, because the basins are adapting in order to reach their equilibrium. The position and existence of tidal divides (tidal watersheds) are affecting this equilibrium state. However, tidal divides are studied insufficiently to understand their behaviour. In this thesis, a first step is made to get more insight in tidal divides in general, but also in the tidal divides present in the Dutch Wadden Sea.

To study the parameters influencing the location of the tidal divide, two basins are schematized to a rectangular channel with at each side an incoming tidal wave. These two incoming waves can differ in amplitude and phase. It turned out that a distinction between two cases can be made: a linear case with very low wave amplitudes and flow velocities, in which the bottom friction is neglected; and a nonlinear case with higher wave amplitudes and velocities resulting in a dominant role of the bottom friction.

The tidal divide is shifted towards the channel end with the largest wave amplitude or the end where the wave enters last. If the phase difference and/or wave amplitude ratio between the two incoming waves is too large, there is no tidal divide at all. The limit of the phase difference for the Wadden Sea means that the barrier islands should have a certain length and/or that the basin should be relatively shallow. In the linear case, the difference in amplitude between the two waves is most important in determining the location of the tidal divide. The contribution of the phase difference is minimal. When bottom friction becomes dominant, the phase difference is governing the position of the tidal divide and the influence of the amplitude ratio is very small.

The depth of the channel is an important parameter, because it influences the importance of the bottom friction. When the channel gets wider towards the middle, the surface elevation is increased and the tidal divide is also kept at the middle of the channel. In the Wadden Sea the tidal range is larger in the back of the basins due to the standing character of the wave, but probably also due to the increasing cumulative width of the branches of the channel system. A longer channel results in less strict conditions for the amplitude ratio and phase difference. More research on the influence of the basin geometry on the position of the tidal divide is needed.

A lot of different definitions and names are used to indicate tidal divides. In this thesis, a distinction is made between a hydraulic tidal divide and a morphological tidal divide. A hydraulic tidal divide is the line splitting the basins in terms of drainage. Engineers are looking for a clear line, because then the hydraulic tidal divide can be used as a basin boundary. In reality there is no line, which makes it difficult and arbitrarily to define a line. After considering multiple definitions for the hydraulic tidal divide, it was concluded that the standard deviation of the flow velocity can best be used to define the hydraulic tidal divide. The fact that the hydraulic tidal divide is used as a basin boundary implies that there always is a location where the hydraulic tidal divide can be defined best, as long as there occurs a (partially) standing wave in the basins.

The morphological tidal divide is the footprint of the hydraulic tidal divide on the bed and indicates where the hydraulic tidal divide is or has been. In the Wadden Sea, the morphological tidal divide has the shape of a spine. The centre line of this spine does not necessarily coincide with the highest bed level. The height of the morphological tidal divide can tell something about the equilibrium of the basins.

The hydraulic and morphological tidal divide can move due to changing circumstances, like closure of a part of the basin. The hydraulic tidal divide can move instantaneously, but its shift is bounded by the morphological tidal divide. The morphological tidal divide first has to be lowered by increased flow

velocities and then the hydraulic tidal divide can move more freely. The morphological tidal divide then heightens again at the new location of the hydraulic tidal divide. This behaviour is illustrated by the tidal divide between Marsdiep and Vlie and shows the importance of the initial bathymetry for the evolution of tidal divides. If the circumstances change more gradually, as happens in the eastern Wadden Sea, the morphological can keep up with the movement of the hydraulic tidal divide more easily.

At this moment, the hydraulic and morphological tidal divides in the Wadden Sea have more or less the same position. Due to the closure of the Zuider Sea, the tidal divide between Marsdiep and Vlie has undergone the largest changes and moved in northeast direction. The Marsdiep basin has increased in size at the cost of the Vlie basin. Further expansion of the Marsdiep is probably locally blocked by the Pollendam. Over the last 80 years, the Eierlandse Gat basin has increased in size. The size of the Borndiep is more or less stable, although the tidal divides bordering it have moved eastward. The morphological tidal divides are all getting higher to compensate for increasing sea level rise, but probably also to ensure a more stable equilibrium.

When the analytical approach is applied to the Wadden Sea, it turned out that the magnitude of the tidal ranges in the inlets of the Dutch Wadden Sea and the phase differences between the inlets is such, that the properties of the tidal wave do influence the position of the tidal divide. Next to this the analytical approach showed that the tidal divides could only come into existence due to the limited depth of the sea behind the islands.

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1. Introduction

Tidal basins exist all over the world and are rich environments due to a large diversity in flora and animal species. Also people generally prefer to life in coastal zones and benefit from the tidal basins by for example recreation and fishing. The Wadden Sea is an example of multiple adjacent tidal basins in the Netherlands. A better understanding of the physical processes in the Wadden Sea can help us to sustain this ecosystem and to manage it in a more thoughtful manner. The Dutch Wadden Sea has already been subject of numerous studies to understand the effects of human interference such as the closure of the Zuider Sea, sand and shell mining and gas extraction, but also to natural forcing like sea level rise. These aspects do not only influence the system itself, but have also resulted in a sediment demand of the Wadden Sea. These sediments are imported from the barrier islands, ebb-tidal deltas and coast of Holland. (Stive and Eysink, 1989) In this way the primary coastal defence of this region is affected and large scale nourishments are carried out to compensate this erosion. This behaviour and response show that a better understanding of the behaviour of the Wadden Sea is of vital importance both for ecology and flood protection.

1.1. Problem description

Tidal basins are believed to have a final equilibrium state, which for instance consists of a certain amount and volume of flats and channels. This equilibrium is dynamic, which means that channels and flats inside the basins and barrier islands can move. After human interventions, like closure of part of the basin, a new equilibrium will be established. Also increasing sea level rise affects the equilibrium. The final equilibrium state is an important aspect of the tidal basins, because it gives insight in the behaviour of the system and also determines the total sediment demand of the Wadden Sea. A lot of studies have been carried out to predict the equilibrium state of the Wadden Sea, but the equilibrium is dependent on a lot of interrelated factors.

The final equilibrium state assumes that all basins are operating separately, i.e. there is no exchange of water and sediments between the basins. This implies that each basin must have a boundary, separating it from other basins. Tidal divides are mostly used as basin boundaries, because of the lower flow velocities and the more elevated bed level. Figure 1.1 is a sketch of adjacent tidal basins with the channel systems and the tidal divides.

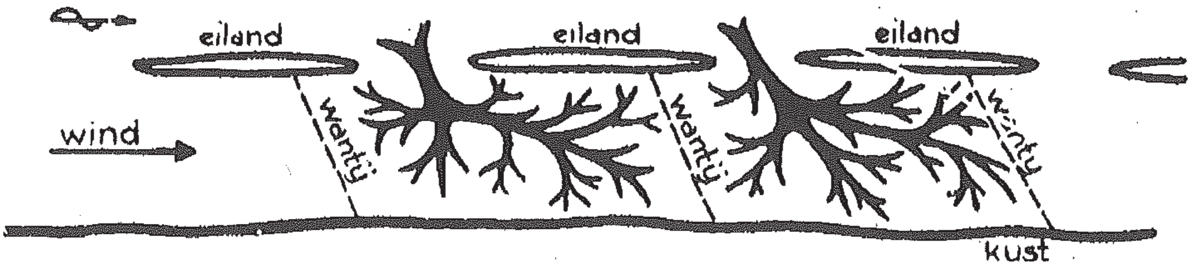


Figure 1.1 Sketch of tidal basins with tidal divides (=wantij) (van Veen, 1950)

The location of the tidal divides determines the surface area of the basin, which is an important parameter in the equilibrium relations of the basins. The equilibrium of the basins is sensitive to small changes in the surface area. The location of the tidal divides is not fixed and not known on beforehand. From observations it is known that tidal divides are moving. From review of literature (see chapter 2.3) it is known that the height of the tidal divides also tells something about the equilibrium of the basins. Several studies already mentioned the importance of the existence and position of tidal divides on the evolution of the basins. However, tidal divides are still insufficiently studied to completely understand their existence and development. Hence, to be able to forecast the future evolution of a series of tidal basins like the Wadden Sea more insight in tidal divides is important.

1.2. Research questions

The review of literature showed which aspects of tidal divides are interesting to study in this thesis. These aspects are covered by the following research questions:

1. What is a tidal divide?

2. Under what conditions a hydraulic tidal divide can be present?

3. How do tidal divides manifest themselves in the Dutch Wadden Sea?

4. Why do the hydraulic and morphological tidal divides between de basins move?

In the research questions a distinction between a hydraulic and morphological tidal divide is already made. The hydraulic tidal divide is indicated by low flow velocities. Morphological tidal divides can be recognized by an elevated bed level. A more detailed description is given in chapter 2.4 and 4.

1.3. Research approach

The research started with a review of literature, which showed what aspects of tidal divides are still not fully understood. The literature is also used as background for further research.

To investigate the influence of different parameters on the position of the hydraulic tidal divide, first a very simple case is considered. Two basins are schematized by a rectangular channel, with at both ends an incoming wave. The following parameters are studied with this configuration:

- the influence of the different tidal ranges at both channel ends (=wave amplitude ratio)
- the influence of the phase difference between the two waves
- the influence of the bottom friction
- the influence of the basin geometry: length, width and depth.

The effect of wind and waves will not be treated in this thesis, because the research time is limited. Other interesting parameters which might have an influence on the position of the tidal divide, are for the Wadden Sea case the influence of the increasing fresh water discharge near Kornwerderzand and the effect of increasing sea level rise. The fresh water discharge is mixed and probably not affecting the tidal divide to a large extend. Therefore this topic is not considered in this thesis. The effect of sea level rise might be translated into increased tidal range and water depth and will be answered qualitatively.

Because the rectangular channel is a rough simplification of reality, the Wadden Sea will be used as a case study. A definition of tidal divides which is applicable to the Wadden Sea will be researched. After a good definition has been selected, the tidal divides in the Wadden Sea will be studied in time. Detailed measurements of the bathymetry of the last 80 years are available and these will be compared to each other to see the changes in the morphological tidal divides. The bathymetry of the last 80 years is also available in the software package Delft3D and this model will be used to study the changes in hydrodynamics (hydraulic tidal divides). This information will be used to answer the question how and why tidal divides move in time.

Finally the theory gained with the simplified channel case is compared to the situation in the Dutch Wadden Sea, to see what conclusions can be drawn.

1.4. Thesis outline

This thesis will start with background information on the Dutch Wadden Sea. The historical evolution of the Wadden Sea will be described and relevant studies are summarized. At the end of chapter 2 a brief description of a hydraulic and morphological tidal divide will be given, which is satisfactory for the first part of the thesis.

In chapter 3 the simplified channel case is considered, which gives good insight in the parameters determining the position of the hydraulic tidal divide.

Chapters 4 and 5 focus on the Wadden Sea. A more detailed description of hydraulic and morphological tidal divides is given and the changes of the divides are studied in time.

In chapter 6 the theory of the simplified channel case will be applied to the Wadden Sea and some conclusions on tidal divides in the Dutch Wadden Sea will be drawn in a qualitative way.

2. Background on the Dutch Wadden Sea

The Wadden Sea stretches all the way from Den Helder at the Dutch coast to Denmark, see Figure 2.1. The shallow sea has a large amount of tidal flats and is sheltered by multiple barrier islands. Especially the tidal flats attract a lot of animal species and the area is an important area for bird migration and breeding. Also people benefit from this rich environment, for example by recreation, fishing and the mining of sand, shells and salt and gas extraction. Due to its versatility, the Wadden Sea is subject to a lot of, sometimes conflicting interests, see Figure 2.2.

Figure 2.1 Tidal flats and channels in the Wadden Sea, artificial satellite image with low water level everywhere (source: www.waddensea-secretariat.org)

Figure 2.2 Different aspects of the Wadden Sea (source: Google Images)

2.1. General characteristics

In the Dutch Wadden Sea, five barrier islands and five tidal basins can be distinguished, see Figure 2.3. From west to east these islands are Texel; Vlieland; Terschelling; Ameland; and Schiermonnikoog. The islands are separated by tidal inlets, which connect the back-barrier basins to the North Sea (from west to east: Texel inlet/Marsdiep; Eierlandse Gat; Vlie inlet; Borndiep/Amelander Inlet; Pinkegat; and Zoutkamperlaag). The tidal wave enters the Wadden Sea via the inlets and meets inside the Wadden Sea behind the barrier islands. At these locations a tidal divide or watershed might be present. With increasing distance from the inlet, flow velocities decrease and sediments are able to settle. This creates tidal flats or a morphological tidal divide between the adjacent basins.

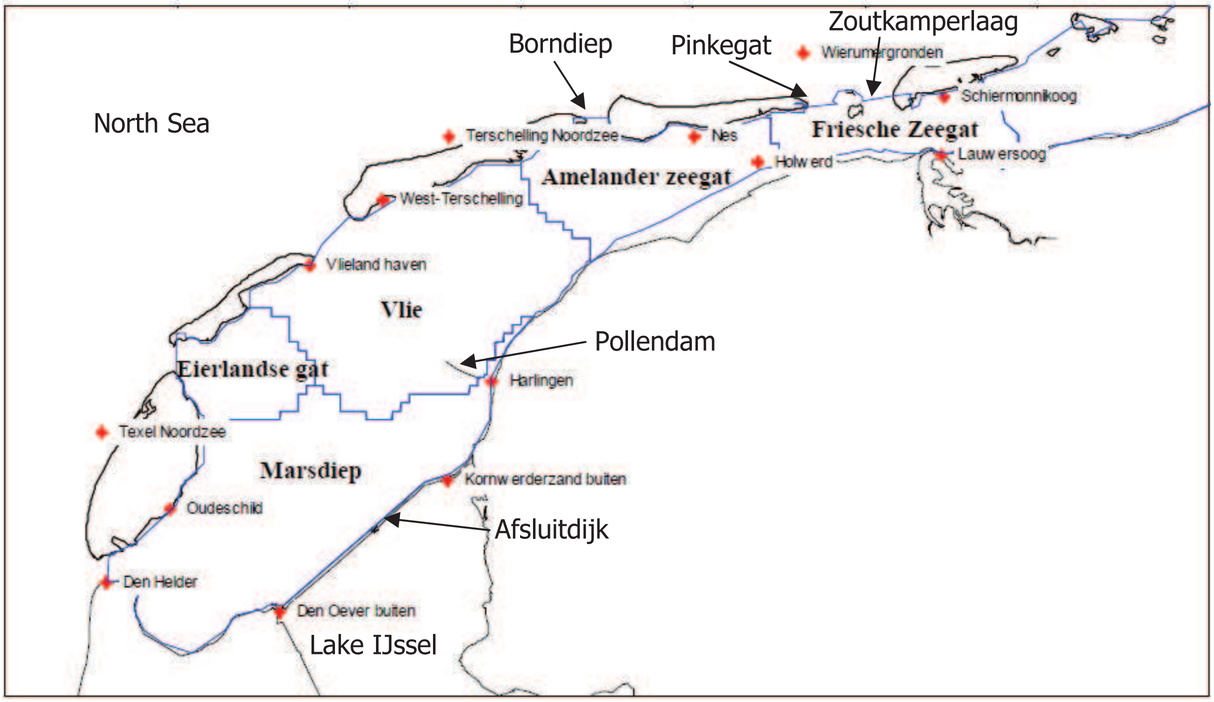


Figure 2.3 Basins in Dutch Wadden Sea (Van Geer, 2007)

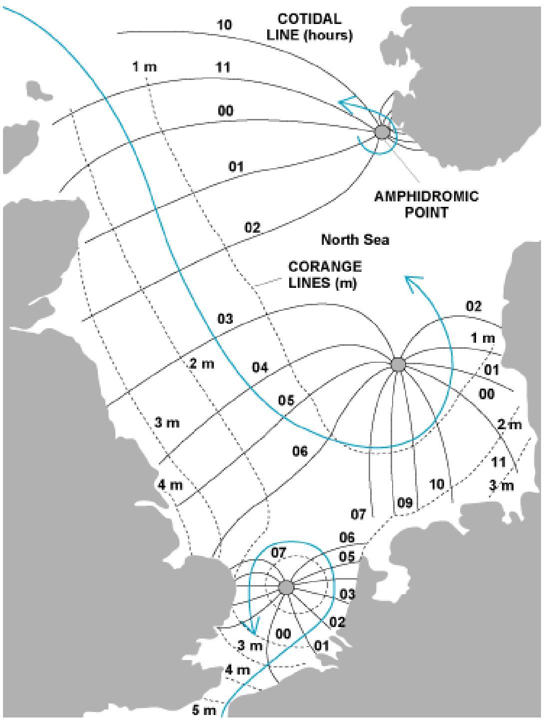


Figure 2.4 Amphidromical points in the North Sea (source: accessscience.com)

The tide in the North Sea is propagating counter clockwise around three amphidromical points, see Figure 2.4. At these points the tidal elevation is close to zero. Along the Dutch coast, the tide moves from the Texel inlet in the west to the Frisian inlet (consisting of Pinkegat and Zoutkamperlaag) in the east, which means that the tide enters at the most westerly inlet first. According to van Veen (1950) amongst others, this results in an eastward shift of the tidal divides. This phenomenon is enhanced by the prevailing wind direction, which is coming from southwest (van Veen, 1950). In addition, the tidal range is increasing from the Texel inlet to the Frisian inlet due to the location of the amphidromical points in the North Sea. Table 2.1 gives an overview of the tidal elevation at various measuring stations in the Wadden Sea for a couple of days. The locations of the measuring stations are indicated in Figure 2.3.

Den Helder		Vlieland Haven		Harlingen		Nes	
Time	Water level in [cm] *	Time	Water level in [cm] *	Time	Water level in [cm] *	Time	Water level in [cm] *
4:10	63	5:25	85	1:06	-81	0:29	-94
10:24	-60	11:55	-81	6:05	99	7:05	106
16:10	54	18:04	77	13:46	-76	13:16	-93
23:05	-69			18:34	90	19:35	99
5:40	61	0:24	-89	2:21	-84	1:50	-100
11:25	-64	6:56	86	7:26	98	8:05	107
16:45	65	13:06	-87	14:56	-80	14:19	-98
		19:26	90	19:50	104	20:35	111
0:30	-74	1:46	-98	3:36	-89	2:56	-110
7:05	59	7:56	87	8:36	98	9:05	108
12:44	-69	14:05	-95	15:56	-85	15:22	-105
17:37	73	20:16	101	20:55	116	21:25	122
1:36	-80	2:35	-105	4:30	-93	3:56	-119
5:24	56	8:46	86	9:14	96	10:06	107
13:51	-75	14:56	-100	16:46	-87	16:12	-110
20:00	79	21:06	108	21:46	124	22:10	130
2:32	-82	3:26	-107	5:22	-92	4:40	-122
5:50	54	9:25	85	10:10	93	10:50	104
14:35	-77	15:39	-104	17:26	-88	16:56	-112
20:34	84	21:33	111	22:26	129	22:56	134

Table 2.1 Water levels in measuring stations in the Wadden Sea.
Data from watersportalmanak.nl, 1-5 January 2011. New moon at the fourth day at 10.03 AM. *w.r.t. NAP

The tidal wave consists of several tidal components with different amplitude and phase. Linear combinations of these components give rise to the spring-neap tidal cycle, which is a result of the interaction between moon and sun attractive forces. Non-linear interactions create overtides which give rise to tidal asymmetry. Inside the basins, the basin geometry, bottom friction and tidal amplitude - water depth ratio influence the tidal asymmetry. This asymmetry involves a shorter rising than falling tide period. If the same amount of water has to be exported as is imported, the flood velocities must be higher than the ebb velocities. Since the sediment transport is proportional to a higher order of the flow velocity, more sediments will be imported than exported. Also the duration of slack waters is important for (fine) sediment transport. When the duration of the slack water period before ebb is longer than the low water slack before flood, the sediments at high water slack have more time to settle and thus less sediment will be exported by the ebb-flow. (Lecture notes of Stive et al., 2006) In this way tidal asymmetry has an important contribution to the sediment transport in the Wadden Sea.

A tidal basin is bordered by barrier islands, tidal divides and/or by land, see Figure 2.5. At the seaward side of the inlet, an ebb-tidal delta is formed. The ebb flow leaving the basin is slowed down as it flows back into the North Sea and sediment is deposited at the foreshore, creating the ebb-tidal delta. The volume of the ebb-tidal delta is defined as the total volume of sediments above the fictitious sea bottom in case there would be no inlet. Inside the basin, a distinction between channels and flats can be made. Channels are the wet parts of the basin during mean low water (MLW) and are defined by the channel volume (the total water volume below MLW) and channel area (wet surface area during MLW). For inter-tidal flats the volume is defined as the volume of sediment between mean high water (MHW) and MLW and the surface area is defined as the dry surface area at MLW. The basin surface area is defined as the total wet surface area at MHW.

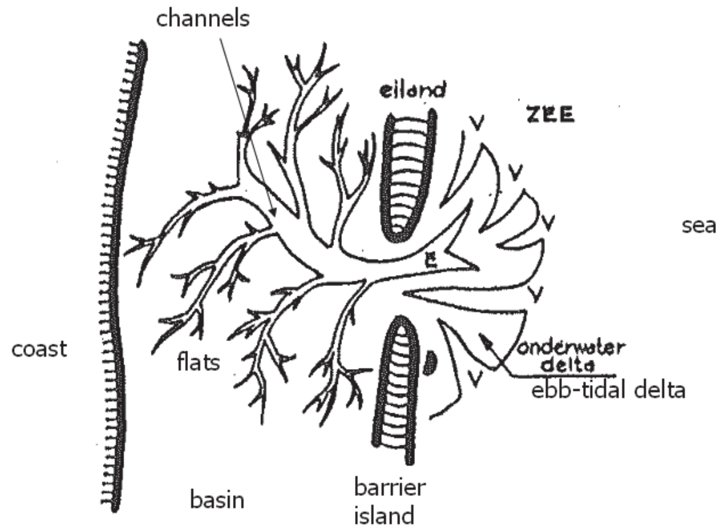


Figure 2.5 Different elements of a tidal basin (van Veen, 1950)

Tidal basins can only exist if there is a certain amount of relative sea level rise in relation to a certain amount of sediment supply. The relative sea level rise is the sum of the absolute sea level rise and the land subsidence, which is also caused by for example gas extraction. If the sediment supply is larger than the demand, the basins will fill up and a closed coastline will be formed, as has happened with the coast of Holland in the past. If the relative sea level rise is too fast and the sediment supply is smaller than the demand, the Wadden Sea will drown and the tidal flats will disappear. If the demand equals the supply, a (dynamic) equilibrium can exist (Nichols, 1988). The current policy is to maintain the 1990 coastline by execution of large-scale nourishments. The supply of sediment at the Dutch coast is artificially changed by these nourishments.

2.2. Historical perspective

In this section, the Dutch Wadden Sea will be studied from a historical perspective. This information is extracted and summarized from Oost & Kleine Punte (2004), who focuses on the western Wadden Sea. Analysis of the historical changes in the basins gives a good overview of the long-term evolution of the Wadden Sea. Oost & Kleine Punte (2004) describe the evolution of the channels and flats of the Marsdiep and Vlie in detail. This also gives good insight in the evolution of the tidal divide between Marsdiep and Vlie.

About 10.000 years ago, the last Ice Age ends and a warmer period begins. The sea level is about 140 m lower than the present level and the North Sea is a large plain. The Western Wadden Sea at that time is an elevated area with a clayey soil (Pleistocene High), surrounded by peat deposits, sand and clay. The increasing temperature causes the sea level to rise and the coast to retreat. At some locations, the sediment supply is sufficient to counterbalance the sea level rise or at some locations even to extend the coast in seaward direction.

In the Eastern Wadden Sea, the first barrier islands are formed around 5000 B.C.. Due to continuous sea level rise, the barrier islands and the coast shift in landward direction. Later, the sediment supply is sufficient to extend the coast in seaward direction. The Western Wadden Sea still is an elevated area, functioning as a barrier behind which peat layers can easily grow. The Lake IJssel is a fresh water lake at that time, called Lake Flevo (later called Almere), which is connected to the North Sea via the river Vlie.

From around 0 A.D., the influence of the sea increases and the Vlie estuary widens. Human interference like the excavation of peat and dewatering of land for agricultural purposes causes land subsidence and make it more vulnerable to flooding. Around 1200 A.D. Lake Flevo turns into a marine environment due to peat layers which are washing away, creating the Zuider Sea. The islands Texel and Vlieland are still connected to the mainland, although the inlets of Eierlandse Gat and Marsdiep are starting to develop, see Figure 2.6. The tidal range in the Marsdiep is quickly increasing, widening the inlet. The Vlie, which was until that moment the only connection between Lake Flevo and the North Sea, is losing part of its discharge and tidal prism to the Marsdiep. A situation in which the Vlie and the Marsdiep are the two important channels in the Western Wadden Sea is developing and this configuration is trying to reach an equilibrium. The increasing tidal prism through the Marsdiep is moving this inlet southward. The Vlie inlet is also not stable and is shifting in easterly direction. Around 1250 A.D. the Eierlandse Gat splits the islands Vlieland and Texel, and develops to a smaller tidal basin.

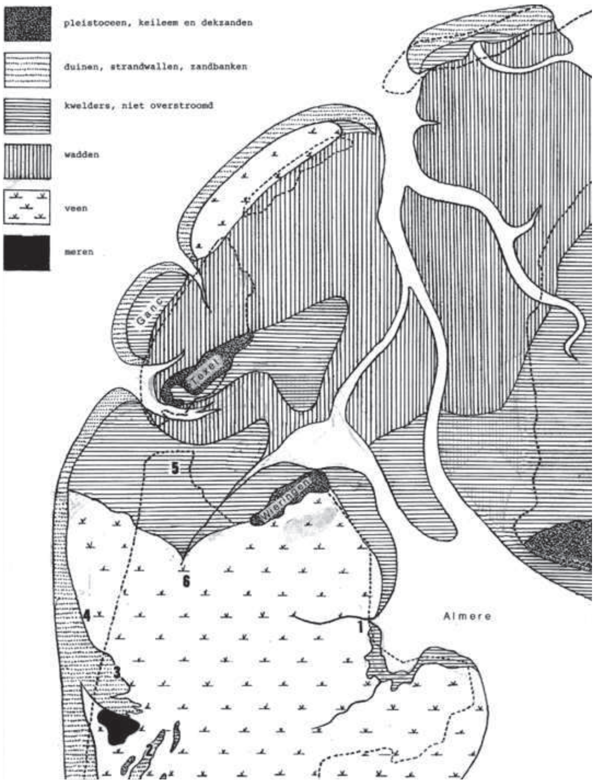


Figure 2.6 Western Wadden Sea 800 A.D. (Schoorl, 1999)

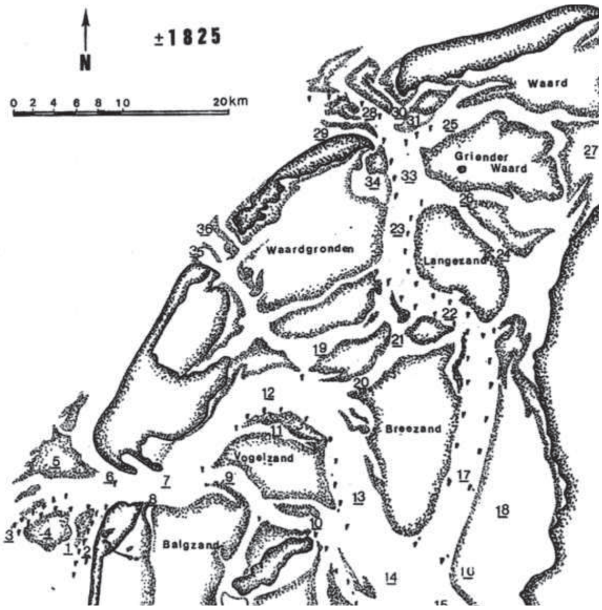


Figure 2.7 Western Wadden Sea 1825 A.D. (Schoorl, 1999)

About the evolution of the Eastern Wadden Sea in the period 0-1300 A.D. not much is known. There must have been barrier islands with a broad strip of tidal marches behind it. People start to build mounds to live on and the inlets between the barrier islands first widen (Lauwers Sea and Dollard are formed), and then the bays accrete again. People start to build dykes and regain land from the sea.

In the period 1600-1900 A.D. the Western Wadden Sea is not changing substantially and a dynamic equilibrium exists, see Figure 2.7. From the Marsdiep the channel Texelstroom is flowing into the Wadden Sea in north-eastern direction and deflecting in south-eastern direction where the Vlieter and Doove Balg are the most important branches. (See Figure 2.8 for the location of the channels mentioned in this paragraph.) At the inlet of the Marsdiep also a southern channel is present, the Balg, which is splitting in the Amsteldiep and Zwin. The Zwin at its turn is consisting of the Wierbalg and Visjagersgaatje. The Balg is a flood channel of the Texelstroom and is fading due to the formation of a new flood channel, the Malzwin. The channels Vlieter, Wierbalg and Zwin are moving eastward. The Vlie is flowing all the way into the Zuider Sea via the Middelgronden. The channels of the Vlie and Marsdiep meet in the Zuider Sea were they are merged into one tidal wave, see figure 2.7 and figure 2.9. The configuration of the channels in the Western Wadden Sea is relatively stable and channels are only moving naturally. The closure of the Zuider Sea is bringing major changes, as will be described in the next paragraphs.

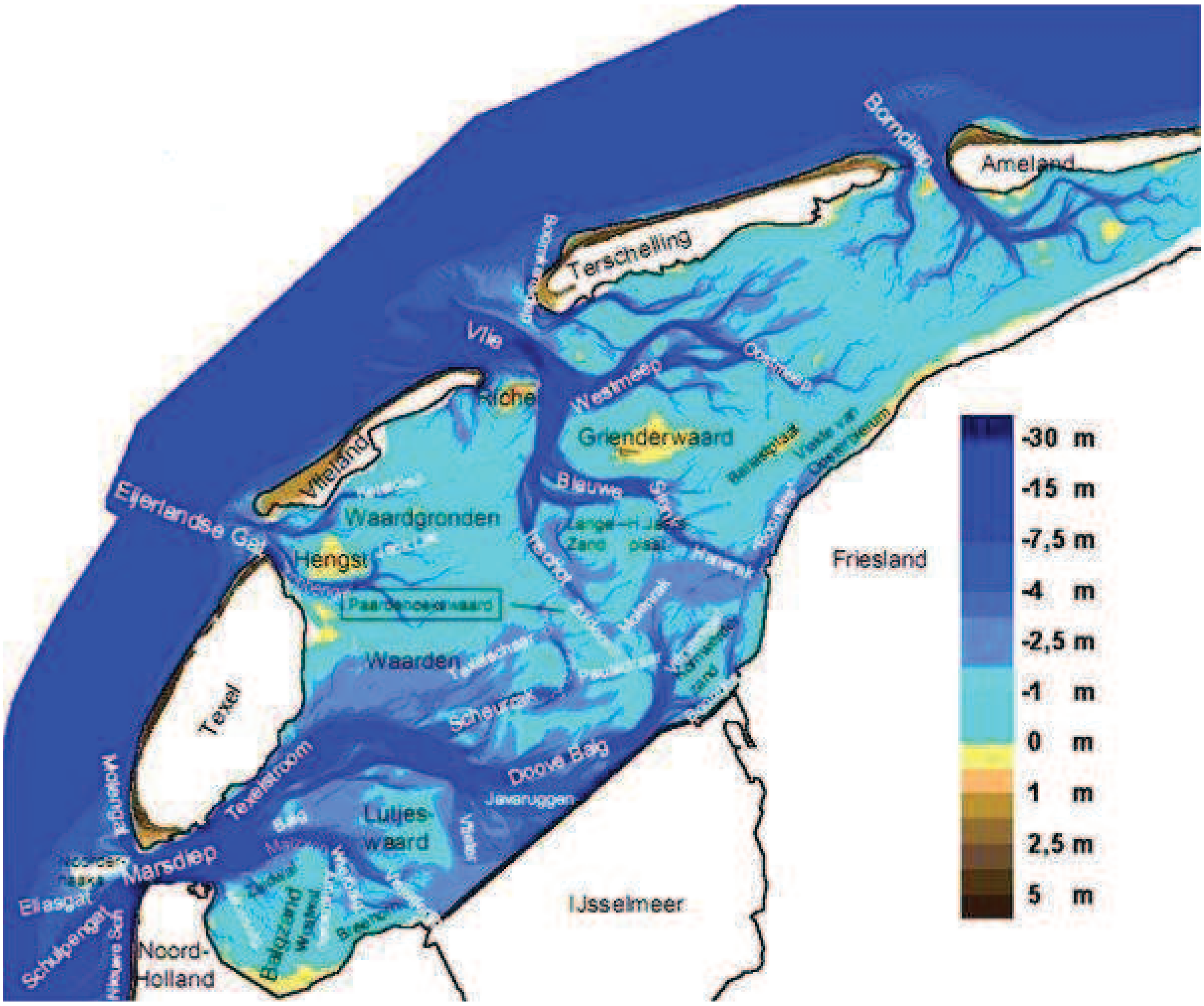


Figure 2.8 Dutch Western Wadden Sea with its channels and flats (Oost & Kleine Punte, 1994)

The construction of the Afsluitdijk (1925-1932) cut off the Zuider Sea from its inlets and turned it into the fresh water Lake IJssel, disturbing the dynamic equilibrium in the Western Wadden Sea to a large extend. The surface areas of the tidal basins of the Marsdiep and Vlie were drastically reduced. The Afsluitdijk, with its length of 32 km, crossed the main channels the Vlieter and the Middelgronden and several smaller channels. Despite the reduction of the basin area, the tidal prism increased due to the increased tidal range after construction of the Afsluitdijk.

The increased tidal prism changes the orientation of the outer deltas of the Marsdiep, Eierlandse Gat and Vlie inlet, which are turned towards the direction the tide is coming from (southwest). Inside the Marsdiep basin, the orientation of the Texelstroom did not change substantially, because the north-east slope of the channel consists of a stiff clay layer (in Dutch: keileem). The channel moved slightly northwards (Elias, 2006). The increased tidal volume at the eastside of the basin deepened the channel Texelstroom. The Waarden, located in the line of the Texelstroom behind the bend in south-eastern direction, are deepening since the closure of the Zuider Sea and a new flood chute Texelschaar is developing in this area. The closure of the Zuider Sea reduced the tidal prism in the area in which the Amsteldiep, Malzwin and Wierbalg are located and here sedimentation took place, heightening the whole area. Also a morphological tidal divide has been formed, dividing the flat Balgzand. The Lutjeswaard has not changed a lot, but has only become shallower at its western tip. The channel of the Vlieter has also become shallower. The channels of the Javaruggen are filled up and in this area a channel parallel to the Afsluitdijk has been formed. The channel Doove Balg has deepened after construction of the Afsluitdijk, its position remained the same. In the area north of the sluices at Kornwerderzand, the tidal range increased and channels in this area, which prior belonged to the basin of the Vlie, are now part of the Marsdiep basin. The channel Verversgat extended in north-eastern direction.

Near the tidal divide between Vlie and Marsdiep, the flat area enlarged and the whole area became shallower. Directly after the closure, there was no connection between the Boontjes and other channels. This caused sedimentation in the Boontjes which continued until 1949. A breakthrough of the Breezand connected the Boontjes with the Doove Balg and this resulted in a deepening of the Boontjes again. The rise of the tidal flats in this area resulted in a narrower channel Boontjes. The sill in the Boontjes became higher after the closure of the Zuider Sea. After dredging in 1957, sedimentation took place which partly reduced the navigational depth again. Since the eighties, the area did not change substantially.

The tidal flats around the channels Molenrak and Hanerak have also become higher and the channels remained at the same depth. A new flood chute, the Paulschaar, has formed after the closure of the Zuider Sea and the eastward extension of this channel is still going on. Also the flood chute Texelschaar is extending eastward and is already connected to the Zuidoostrak. It is possible that the Texelschaar develops into one of the main channels in this area and probably causing the Scheurrak to disappear.

The Eierlandse Gat is subject of minor changes. The outer delta became oriented in a more westerly direction. The tidal divide between the Vlie basin and the basin of Eierlandse Gat is also moving in eastward direction. The role of the Eierlandse Gat as minor system squeezed in between the basin of the Marsdiep and the Vlie is expected to remain in the future.

The channels in the Vlie basin have more or less a stable position. In the south-western part of the basin the channels Inschot and Zuidoostrak are retreating due to the closure of the Zuider Sea and the increased dominance of the Marsdiep basin in this area. Also the Omdraai, Oude Vlie and Jetting are becoming shallower and narrower. The Vlie inlet gorge shows a stable configuration, which is enforced by its position in a stiff clayey subsoil. North of Harlingen, a large flat called the Vlakte van Oosterbierum is extending and getting higher. Since the closure of the Zuider Sea the flat Ballastplaat has been moving in north-eastern direction and it merged with the Vlakte van Oosterbierum at the end of the nineties. By dredging and the construction of the Pollendam, the navigation channel between the harbour of Harlingen and the North Sea is kept at depth.

Considering the past evolution of the basins, a further retreat of the south-western channels of the Vlie basin is expected. Whether the channels of the Marsdiep basin continue to expand in the same direction is not clear. Oost & Kleine Punte (2004) state that the Boontjes is in equilibrium and expect no significant changes in the future. Close to the Afsluitdijk infilling of old channels may proceed.

2.3. Relevant studies

Numerous studies concerning the Wadden Sea focus on the equilibrium of the basins. For the equilibrium volumes and surface areas of different elements of tidal basins often reference is made to Eysink (1990). He among others derived empirical relations by the comparison of tidal inlets and basins all over the world. The equilibrium volume and surface area of the elements in the basin are related to the tidal prism or tidal range. The tidal prism is defined as the total volume of water that flows in a basin during flood plus the total volume which flows out during ebb, and is dependent on the tidal range, the total basin surface area and the volume of the tidal flats. Hence, all volumes and surface areas (like the basin area) are interrelated. Eysinks method assumes that tidal basins in equilibrium can be considered as separate basins with each one inlet.

Van de Kreeke (1990) investigated whether multiple inlets can be stable. He schematized the water-level fluctuations in a basin with two inlets as uniform over the whole basin. His research showed that when two inlets are in equilibrium, a small change in the cross-sectional area of the inlet gorge will result in closure of one of the inlets. This study is extended by Van de Kreeke et al. (2008) which investigated the morphological stability of two basins divided by a topographic high (=morphological tidal divide). The sub-basins at either side of the topographic high have different water level fluctuations in time, although uniform throughout the sub-basin. This study confirmed that for a very low topographic high, approaching the case of one basin with two inlets, no combination of inlet cross-sectional areas exists in which both inlets are stable. When the topographic high is higher, the situation approaches two basins with each one inlet and a set of stable equilibriums does exist. From these studies can be concluded that sediments and water can be exchanged as long as basins are not in equilibrium, this is also called a sand-sharing system. In order to reach an equilibrium, a high morphological tidal divide will have to form or an inlet will have to close. The final equilibrium state holds separate basins with each one inlet.

Studies concerning the equilibrium of the basins are motivated by the human interferences. The closure of the Zuider Sea by construction of the Afsluitdijk for example, drastically changed the hydrodynamics and morphodynamics in the Wadden Sea. First, the tidal wave which entered via Marsdiep and Vlie, merged in the Zuider Sea, see Figure 2.9. Due to the fact that the basin was relatively long and shallow, bottom friction had a large reducing effect on the amplitude of the wave. After the closure, the tidal wave is less dampened by bottom friction and is reflected at the Afsluitdijk. The tidal wave developed into a wave with a more standing character. These factors increased the tidal range in such a way, see Figure 2.10, that the tidal prism also increased, despite the reduction of the basin area (Kragtwijk, 2001). The result of these changes is an increased sediment demand of the Vlie and Marsdiep basin, which is needed to reach a new equilibrium.

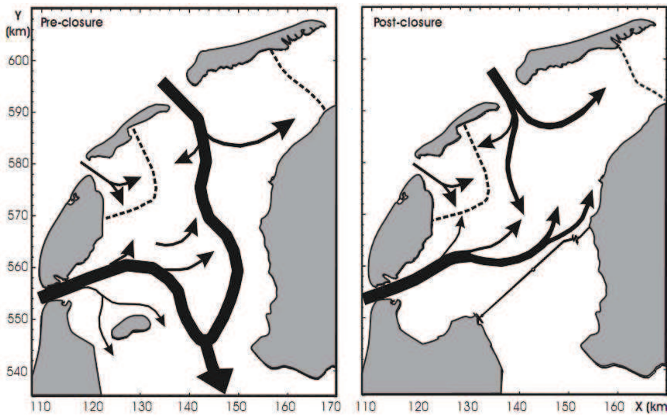


Figure 2.9 Propagation of the tidal wave into the Wadden Sea (left) before and (right) after closure (Elias (2006) adapted from Thijsse (1972))

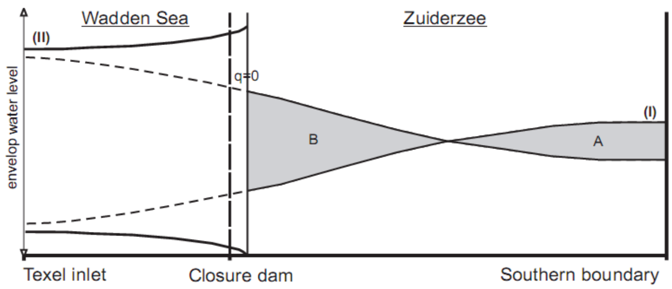


Figure 2.10 Schematisation tidal wave envelop before (I) and after (II) closure (Elias (2006) adapted from Kragtwijk (2001))

There is still discussion going on to which extend the basins of the Marsdiep and Vlie are in equilibrium and have adapted to the situation after the closure of the Zuider Sea. When the equilibrium volumes of the tidal elements are calculated, the ratio between the shoals and channels is very low, indicating that a large amount of sediment is still needed to reach the equilibrium state (Louters and Gerritsen, 1994). According to Van Dongeren and de Vriend (1994) on the other hand, the relative flat area is smaller for larger basins. Measurements show that the Western Wadden Sea is importing a large amount of sediment, which is in line with the equilibrium relations. But the sediment volume change of the Marsdiep basin in time shows a decrease in changes since 1977. From these data can be concluded that the basin is in near equilibrium (Elias, 2006). Kragtwijk et al. (2004) showed that different elements of the systems have different adaptation timescales towards an equilibrium. In the Vlie basin, the delta and flats have reached an equilibrium and the channels are still adapting. This adaptation does not necessarily have to happen linearly, it is possible that an element first overshoots its equilibrium state and later grows towards it again. This might be due to the combination of all elements with different adaptation timescales which have to grow to an equilibrium together, distributing sediments between each other. In addition, large basins generally have a longer adaptation time than smaller ones. Directly after the closure and the disturbance of the equilibrium, a basin reacts very quickly. If time proceeds, the basin approaches its equilibrium state and adaptation slows down. This implies that the basin of Marsdiep is still trying to reach its equilibrium, but this is happening slower than in the first years after closure. Whether the Marsdiep basin is really capable of developing more flat area and whether this is needed to reach an equilibrium is not certain. Of course, this is also dependent on the sediment availability, which governs the adaptation (time) to a new equilibrium.

In the Wadden Sea, the sand-sharing mechanism between the basins is observed. Observations show significant residual flow and sediment transport between the basins of Marsdiep and Vlie. In the period 1985-1997, the ebb-tidal delta of the Marsdiep suffered from erosion and the Eierlandse Gat ebb-tidal delta was subject to minor erosion. The Vlie ebb-tidal delta shows an increased volume in the same period. Major sedimentation took place in the basin of the Vlie and in the Marsdiep basin only a small amount of sediments has been deposited. This is a strong indication that these basins exchange sediments in other to reach an equilibrium (Elias, 2006, p.157-160).

Ridderinkhof (1988) studied the residual flow between the basins of the Marsdiep and the Vlie by schematizing both basins with a flat bottom (i.e. no topographic high). The momentum equation considered neglected the Coriolis force and horizontal turbulent viscosity terms and included a linearized bottom friction term. This research considered three mechanisms influencing the amount and direction of the residual flow:

- the phase differences of the two tidal waves entering the basins;
- the difference in amplitudes between these tidal waves;
- the shape of the basin (deep/narrow vs. shallow/wide).

The study revealed that the residual flow was directed towards the basin where the tidal wave entered last, or towards the basin where the amplitude of the wave was smallest or towards the deeper and/or narrower basin. In case of the Dutch Western Wadden Sea, the amplitude difference and the shape of the basins are dominant over the wave propagation in the North Sea (phase difference). This results is a residual flow from the Vlie basin towards the Marsdiep basin of approximately 900 m^3/s.

Van der Waal (2007) studied the sediment patterns in the Western Wadden Sea with help of the software package Delft3D. Calculations were made to find the equilibrium volumes of all elements in the basins and the bathymetry was adapted to this equilibrium. Computations with this bathymetry show an export of sediment through the Marsdiep inlet. The equilibrium depth of the Texel basin is a lot shallower than the present depth, resulting in a hindered propagation of the tidal wave in the Texel basin and a reduced tidal prism. This results in a shift of the tidal divide towards the Texel inlet. The shift of the tidal divide reduces the flat area in the Texel basin and an import of sediments has to counteract this loss of flat area. This import counteracts the export which is computed with the equilibrium bathymetry and thus the shift of the tidal divides has a stabilizing effect on the transport through the Texel inlet. This is in contradiction with the results of Dastgheib et al. (2008). In this study the long-term morphological evolution of the Western Wadden Sea is simulated with Delft3D using different bathymetries. The bathymetries considered are flat bathymetries and a sloping bathymetry (both no channels and flats) and the real bathymetry of 1998. Their simulation period had a duration of 2100 years and showed that the basins boundaries of Marsdiep and Vlie are moving in eastward direction, which matches the historical evolution as described in section 2.2. Another important conclusion from their study was that the initial bathymetry is very important for the long-term evolutions of the basins.

Van der Waal (2007) also studied the influence of different forcing agents on residual flow and sediment transport. If only the tidal forcing is considered, sediment transport over the tidal divides is limited but the location of the tidal divides is influencing the rate of the transport through the inlets. The combination of the tidal forcing and wave forcing shows that wave forcing is mainly affecting the sediment patterns in the ebb-tidal deltas. The 'stirring-up' effect of the particles is strongest here, while in the basin itself it is limited. Wave induced set-up or set-down of the water level differs in each basin and drives other residual flow patterns than if waves are absent. Wave forcing also showed that for large wave heights (H_s>3m), the sediment transport over the tidal divides increases considerably and equals the magnitude of sediment transport through the inlets. If also wind forcing is taken into consideration, a distinction can be made between large-scale and local forcing. The large-scale forcing can create a water level set-up or set-down which is influencing the tidal prism and the residual flow through the inlets. These residual flow changes are in the same order of magnitude as residual flow induced by tidal forcing. Large-scale wind forcing also drives an additional long-shore current, which affects the residual flow and sediment transport through the inlets. Local wind forcing creates currents in the direction of the wind forcing, which are considerable during storms. The wind-driven sediment transport over the tidal divides however, is significantly underestimated in this simulation. This might be due to the uniform sediment particle distribution which is used, overestimating the smaller particles which are present near the tidal divides.

Van Geer (2007) investigated improvement of the ASMITA model. ASMITA uses the equilibrium relations of the system elements to compute the long-term morphological evolution of the Wadden Sea. One of the outcomes of this thesis was that moving basin boundaries (i.e. tidal divides) results in better model results. Therefore he recommended investigating the movement of basin boundaries in time. He also tried to include sediment transport between the basins in the model, but this was unsuccessful. A better understanding of the physical processes causing the sediment exchange is needed to implement this transport in the model.

From the review of literature the conclusion can be drawn that more insight in tidal divides is important to understand the evolution of the basins. The position of the hydraulic tidal divide determines the surface areas of the basins, which is an important parameter in the empirical equilibrium relations. The height of the morphological tidal divide is a measure for the equilibrium of the basins, because a basin with two inlets (and a low topographic high) is not stable. Review of the literature not only showed the lack of information on tidal divides, but also the uncertainty about the tidal divide between the basins of Marsdiep and Vlie. The basins of Marsdiep and Vlie are still adapting to the closure of the Zuider Sea, and changes in the bathymetry will influence the characteristics and propagation of the tidal wave. This will also have an effect on the morphological tidal divide between the basins and the interaction of the basins by means of residual flow and sediment transport.

2.4. Current definition of a tidal divide

In literature, a tidal divide is also referred to as (tidal) watershed or wantide (which is a literal translation of the Dutch 'wantij'). In this thesis, a distinction between a hydraulic tidal divide and a morphological tidal divide is made.

The **hydraulic tidal divide** is the line splitting the two basins in terms of drainage. The area which is filled and emptied by the tidal wave passing through one inlet, belongs to the basin of this inlet. However, this is not as straightforward as it seems to be. It is possible that an area is filled by the tidal wave entering via one inlet and emptied via another. The position of the hydraulic tidal divide can also be defined as the location where the flow velocities are minimal. Different conditions, for example the moment in the tidal cycle, the wind direction and wind load can change the location where the flow velocities are minimal. Therefore, the minimum of the standard deviation of the flow velocity during a certain period is often used as a definition of the hydraulic tidal divide.

The **morphological tidal divide** might be defined as the location with the highest bed level elevation. The absolute flow velocities and the sediment properties and availability are determining the absolute height of the flats, where the morphological tidal divide is consisting of. Maybe the shifting of the minimum of the flow velocities under different circumstances is also affecting the development of the morphological tidal divide. The morphological tidal divide does not necessarily have to be located at the position of the hydraulic tidal divide, because the divides can move in time (on the long term). Morphological changes are slower than hydrodynamic changes and it is possible that the morphological tidal divide is moving towards the hydraulic tidal divide. The morphological tidal divide on its turn might have an influence on the position of the hydraulic tidal divide.

3. Position of the tidal divide

In this chapter the influence of different parameters on the position of the tidal divide is investigated. To get a clear view on the contribution of all parameters to the position of the tidal divide, two basins are simplified to one rectangular channel with at both ends an incoming wave. The position of the hydraulic tidal divide is investigated, which implies that a morphological tidal divide is absent in the channel and also sediment transport is not considered in this chapter.

First, the position of the hydraulic tidal divide in this channel is obtained analytically. In this analytical approach two cases are considered: a case without friction and a case with linearized friction. Because in this analytical approach some terms in the continuity and momentum equation are neglected and linearized, the results are verified with simulations. These simulations are carried out with the software packages Sobek and Delft3D, which both can execute the computations. The simulations are also used to investigate the effect of geometry variations in the direction of the channel axis, because an analytical approach would in this case result in very long algebraic equations.

3.1. Schematization

As mentioned above, two basins are schematized to a channel, see Figure 3.1. Except for the section where the basin geometry is varied, the channel is horizontal and has a constant width, depth and length. At x=0 the left inlet is present with an incoming tidal wave with wave amplitude $\eta_{x=0}$. At x=L the right inlet is located, with wave amplitude $\eta_{x=L}$ and phase difference φ with respect to the wave at x=0.

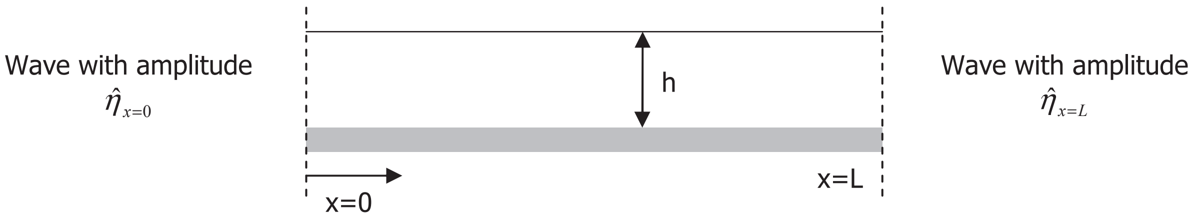


Figure 3.1 Simplified case

The boundary conditions are given by:

$\eta_{x=0}(t) = \hat{\eta}_{x=0} \cdot \cos(\omega t)$ and

$\eta_{x=L}(t) = \hat{\eta}_{x=L} \cdot \cos(\omega t - \varphi)$

The amplitude of the two waves will be represented by the wave amplitude ratio between the two waves, given by:

$$a = \frac{\eta_{x=L}}{\eta_{x=0}}.$$

The channel schematization starts with a length of 10 km, which is in the same order of magnitude as the Wadden Sea (distance between the inlets vary from 20 to 80km). The depth in the Wadden Sea has a large variation over the basin, from up to 40 m in the inlets to zero at the tidal divides. A depth of 5 m is used as a starting point. Tidal ranges vary from 1.2 to 2 m, resulting in amplitude ratios of 1 to 1.2. The phase difference varies from 0.1 to 0.3 rad (≈30 minutes). These parameters in relation to the channel simulations are studied more thoroughly in chapter 6.

3.2. Analytical approach

Below, the analytical approach is briefly described. For a more detailed derivation, see the lecture notes of Battjes (2002) and Wang et al. (2011).

Tidal waves are long compared to the water depth, due to which the pressure can be assumed hydrostatic. Under this condition, the momentum and continuity equation are given by, resp.:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \eta}{\partial x} + c_f\frac{u\,|\,u\,|}{h+\eta} = 0 \qquad [3.1]$$

$$\frac{\partial \eta}{\partial t} + (h+\eta)\frac{\partial u}{\partial x} + u\frac{\partial (h+\eta)}{\partial x} = 0 \qquad [3.2]$$

Under the assumption that the tidal wave is very long and the wave amplitude is small relative to the water depth (η<<h), the flow velocities will be low and the advective inertia term (2nd term in [3.1]) and the 3rd term in [3.2] can be neglected. The friction term can be linearized. The momentum and continuity equation then reduce to:

$$\frac{\partial u}{\partial t} + g\frac{\partial \eta}{\partial x} + \kappa u = 0 \qquad [3.3]$$

$$\frac{\partial \eta}{\partial t} + h\frac{\partial u}{\partial x} = 0 \qquad [3.4]$$

Herein:

$$\kappa = c_f \cdot \frac{|\,u\,|}{h} = \frac{8}{3\pi} c_f \cdot \frac{\hat{u}}{h} \qquad [3.5]$$

By taking the derivative of the momentum equation to x and the derivative of the continuity equation to t, the wave equation with linearized friction term follows:

$$\frac{\partial^2 \eta}{\partial t^2} - c^2\frac{\partial^2 \eta}{\partial x^2} + \kappa\frac{\partial \eta}{\partial t} = 0 \qquad [3.6]$$

The general solution of this equation is:

$$\tilde{\eta}(x) = \eta_1 \cdot e^{-px} + \eta_2 \cdot e^{px} \qquad [3.7]$$

And $\eta(x,t) = \mathrm{Re}[\tilde{\eta}(x) \cdot e^{i\omega t}]$ [3.8]

In these equations:

$$p = \mu + ik = ik_0\sqrt{1 - i\sigma} \qquad [3.9]$$

$$\sigma = \frac{\kappa}{\omega} \qquad [3.10]$$

The complex surface elevation satisfying the boundary conditions is:

$$\tilde{\eta}(x) = \frac{\sinh[p(L-x)]}{\sinh(pL)} + \frac{\sinh(px)}{\sinh(pL)} a \cdot e^{-i\varphi} \qquad [3.11]$$

With $\tilde{a} = a \cdot e^{-i\varphi}$, the complex amplitude at the channel end x=L.

By applying the continuity equation [3.4] again, the flow velocity can be derived.

$$u(x,t) = -\frac{1}{h}\int \frac{\partial \eta}{\partial t}\partial x = \frac{i\omega}{ph}\left(\frac{\cosh[p(L-x)]}{\sinh(pL)} - \frac{\cosh(px)}{\sinh(pL)} a \cdot e^{-i\varphi}\right)\cdot e^{i\omega t} \qquad [3.12]$$

$$\tilde{u}(x) = \frac{i\omega}{ph}\left(\frac{\cosh[p(L-x)]}{\sinh(pL)} - \frac{\cosh(px)}{\sinh(pL)} a \cdot e^{-i\varphi}\right) \qquad [3.13]$$

Because this velocity is expressed as a complex number, the derivative of its modulus will indicate the position of the tidal divide: the tidal divide is located where the derivative is zero. The mathematical elaboration of this method will be very long, therefore it is illustrated by the case without bottom friction. If the bottom friction is neglected, $\sigma=0$ and p reduces to ik_0.
The amplitude of the flow velocity then is:

$$\hat{u}(x) = \frac{\omega}{k_0 h}\sqrt{\left(\frac{\cos[k_0(L-x)] - a\cos(k_0 x)\cos\varphi}{\sin(k_0 L)}\right)^2 + \left(\frac{a\cos(k_0 x)\sin\varphi}{\sin(k_0 L)}\right)^2} \qquad [3.14]$$

By taking the derivative of the flow velocity amplitude to x and making it zero, the following equation follows after some algebra:

$$\tan(2k_0 x) = \frac{\sin(2k_0 L) - 2a\cos\varphi\sin(k_0 L)}{\cos(2k_0 L) - 2a\cos\varphi\cos(k_0 L) + a^2} \qquad [3.15]$$

with

u	flow velocity [m/s]	L	length of the channel [m]
g	gravitational acceleration [m/s^2]	ω	frequency [rad/s] (=2π/T)
η	surface elevation [m]	*a*	amplitude ratio [-]
c_f	friction coefficient [-]	φ	phase difference [rad]
h	water depth [m]	$\hat{u}$	amplitude of flow velocity [m/s]
c	celerity [m/s] ($c_0=\sqrt{gh}$)	k	wave number [-] (=$2\pi/\lambda$)
κ	factor for linearized friction [s^{-1}]	k_0	frictionless wave number [-] (=ω/c)
μ	damping factor [-]	λ	wave length [m]

Equation [3.15] is the analytical expression for the position of the hydraulic tidal divide without friction, depending on the wave amplitude ratio *a*, the phase difference φ, the wave number k_0 and the channel length L. The influence of these parameters is elaborated in section 3.2.1.

The case with linearized bottom friction, see section 3.2.2, will be elaborated by calculating the flow velocities and then taking the minimum. There is no analytical expression derived for the position of the tidal divide as in [3.15].

3.2.1. Case without friction

In this section the influence of the wave amplitude ratio, the phase difference and the relative channel length k_0L is discussed for the case without friction. For the frictionless wave length a value of $k_0=2*10^{-5}$ is taken. The channel has a length of 10 km, unless stated otherwise. Below the influence of each of the parameters is investigated.

If the wave amplitude ratio *a*=1, the channel section has two incoming waves with the same amplitude. In this situation the position of the tidal divide is always located halfway the channel, *independent* of the phase difference φ, see Figure 3.2. This means that in this case a (partially) standing wave will occur, with its antinode always located at x=½L. If the waves enter the channel at the same moment (φ=0), a purely standing wave occurs and the flow velocity at the tidal divide is 0. If the phase difference is increased, the flow velocity at the antinode increases and the wave gets a more propagating character. If φ is equal to k_0L, the wave is purely propagating and no tidal divide can exist.

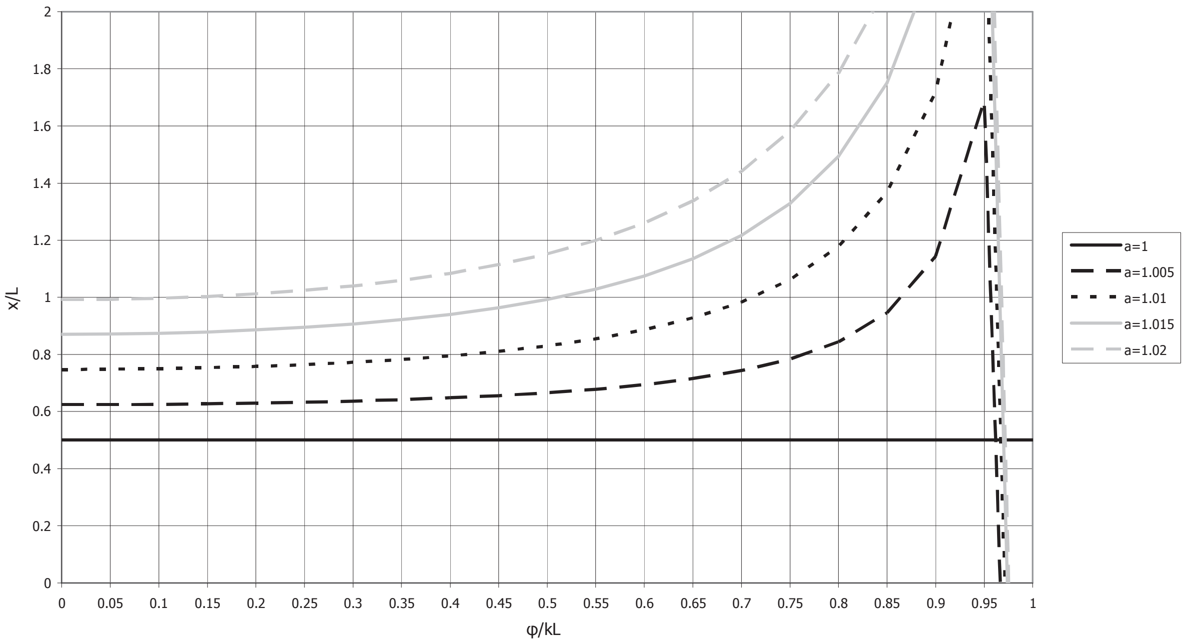


Figure 3.2 Position of the tidal divide versus the relative phase difference (kL=0.2) for increasing wave amplitude *a*
Note that a tidal divide is only present if x/L is in the realistic domain between 0 and 1.

Figure 3.3 shows the flow velocities in the channel increasing due to an increasing the phase difference. With increasing channel length L, the relative phase difference (φ/kL) is decreased and the flow velocities at the position of the tidal divide decrease as well. The variation of the flow velocities over the channel is larger, because the channel is longer.

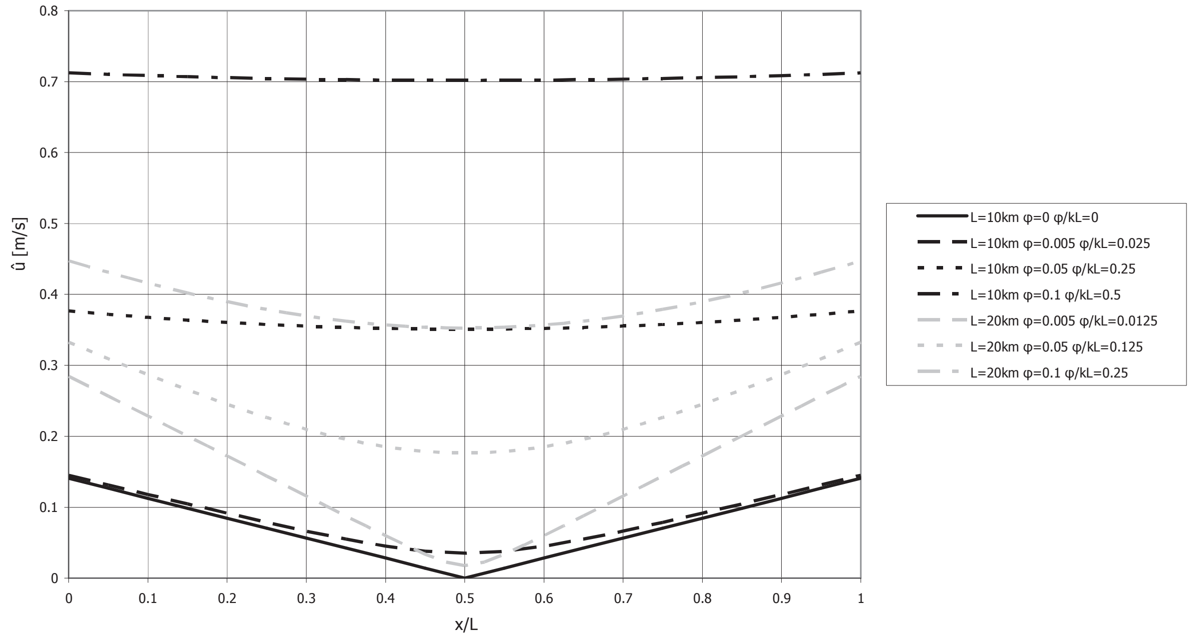


Figure 3.3 The amplitude of the flow velocity for increasing phase difference φ and different channel lengths (L=10 km and 20 km), for equal wave amplitude *a*=1

If the phase difference φ=0 and the amplitude ratio *a* is increased, the position of the tidal divide is shifted towards the channel end with the *largest* amplitude, see Figure 3.2. This is a result of the fact that the flow velocities for standing waves are minimal at the position where the surface elevation has its maximum. With increased wave amplitude at one side of the channel, the maximum surface elevation will also shift towards that channel end. For too large wave amplitude ratios, the tidal divide is no longer located in the realistic domain. So, also the wave amplitude ratio *a* is bounded to a limit.

Figure 3.2 also shows that the larger the value of *a*, the larger the influence of φ: if *a* increases, a stricter condition for φ has to be satisfied to guarantee the existence of a tidal divide. Figure 3.4 shows the sensitivity of the position of the tidal divide to amplitude ratio variation in relation to phase difference variation.

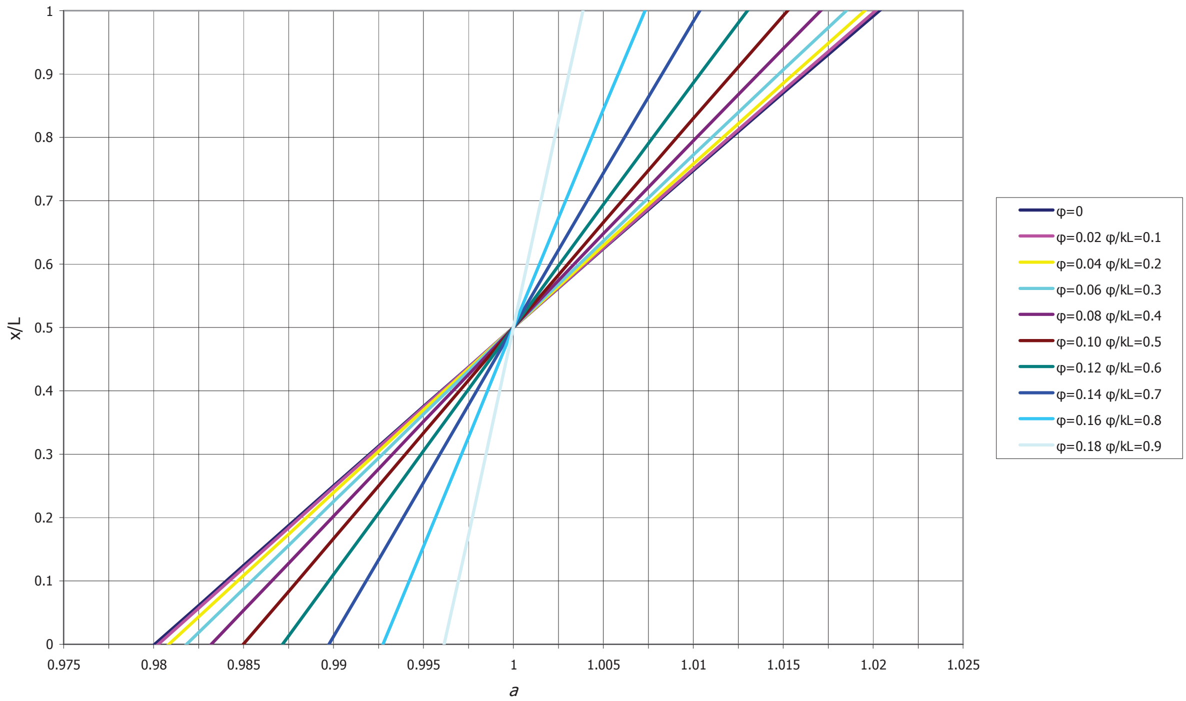
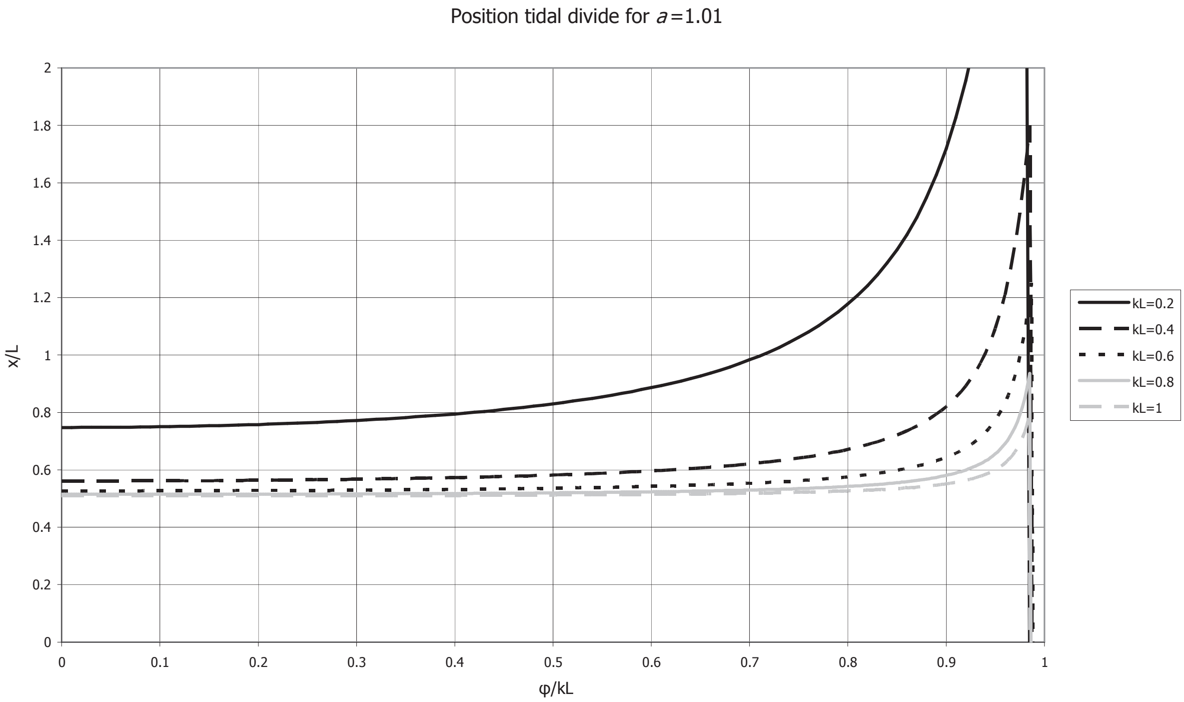


Figure 3.4 Position of the tidal divide versus the amplitude ratio for increasing phase difference φ

Figure 3.5 shows the influence of the relative channel length on the position and existence of the tidal divide. If the channel length is increasing, the conditions for φ and *a* are less severe to satisfy the requirement that the tidal divide is in the domain 0<x<L.



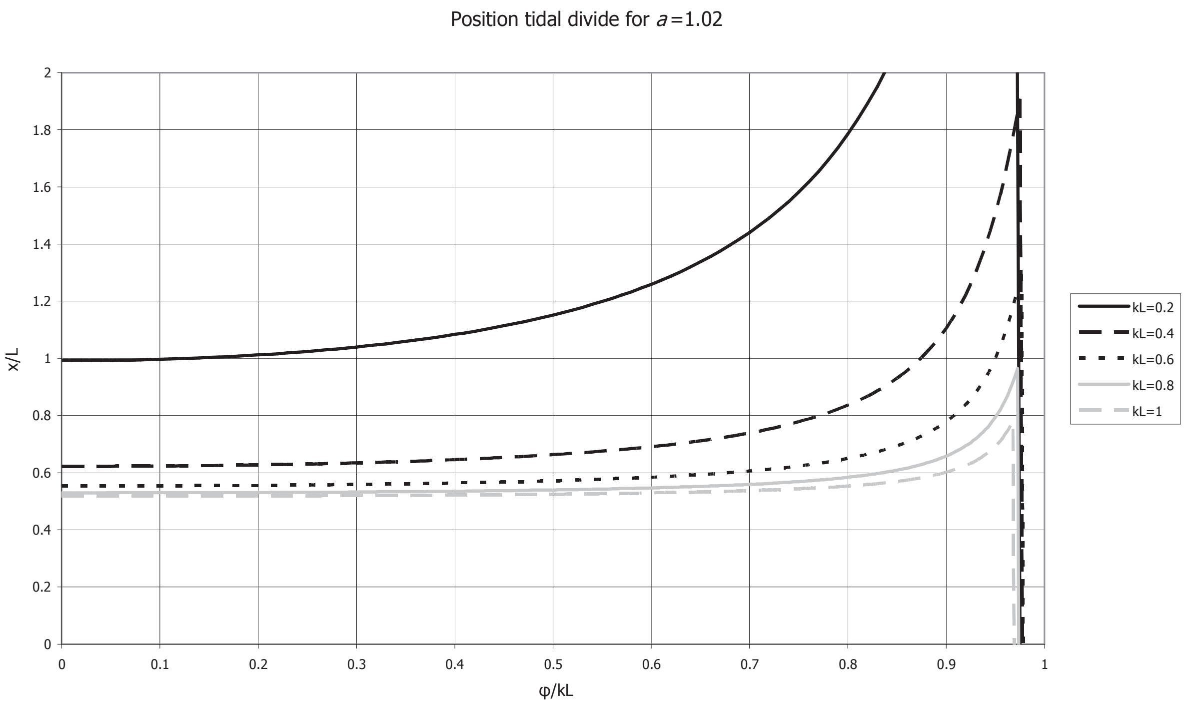


Figure 3.5a and b Position of tidal divide for increasing channel length and increasing phase difference φ, for constant wave amplitude (figure a for *a*=1.01 and figure b for *a*=1.02)

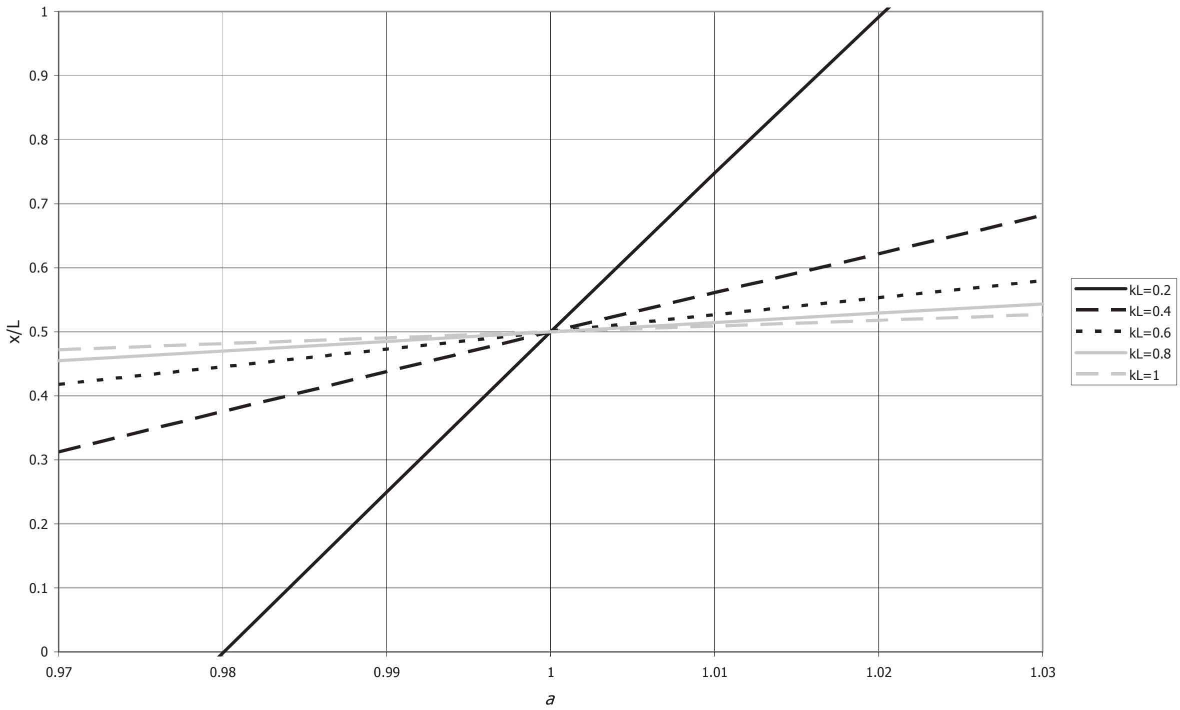


Figure 3.6 Influence of channel length on position tidal divide for φ=0

Figure 3.6 displays that the wave amplitude ratio is not linearly dependent on the channel length. If the channel is longer, the amplitude ratio can differ much more from unity, before the tidal divide shoots outside the realistic domain.

3.2.2. Case with linearized friction

This case holds a calculation with the linearized bottom friction, indicated by the parameter σ, see equation 3.10. For this case the analytical expression for the position of the tidal divide is not derived, but calculations can be done to show the behaviour of the position of the tidal divide for varying wave amplitude ratios and phase differences.

Below the influence of the bottom friction is illustrated by three figures with different values of σ. It clearly shows that the inclusion of bottom friction is resulting in a more dominant role of the phase difference. Comparison of Figure 3.7, Figure 3.8 and Figure 3.9 show the remarkable effect that the condition for φ is first becoming stricter and later less strict for increasing bottom friction ($\varphi<0.2$ for $a=1$ and $\sigma=1$ versus $\varphi<0.25$ for $a=1$ and $\sigma=2$), this is studied in more detail later on. Also, the case without bottom friction shows curved lines, while in the cases with $\sigma>0$ the lines are linear. Apparently, the coupled behaviour between the amplitude ratio *a* and the phase difference φ is only present when friction is neglected. The influence of the wave amplitude ratio is decreasing with increasing bottom friction, as is visible by the contraction of the lines in Figure 3.7 to Figure 3.9 and the flatter slope of the lines in Figure 3.10 for $\sigma=2$.

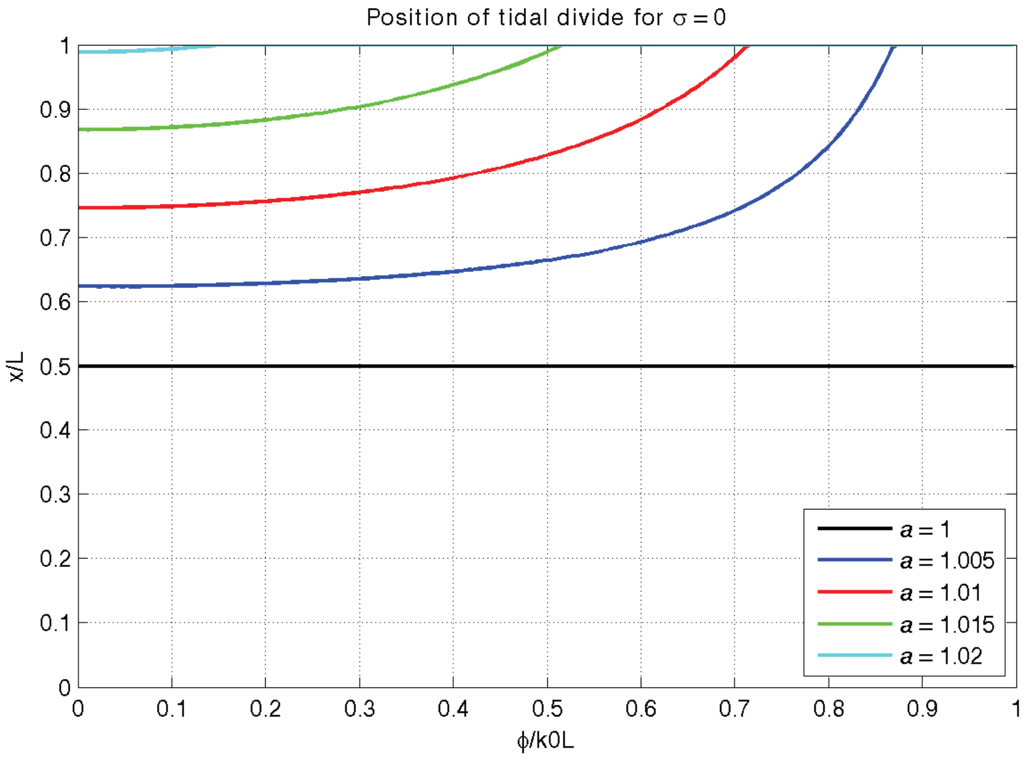


Figure 3.7 Position of the tidal divide versus the relative phase difference (φ/k_0L) for case without bottom friction σ=0 (repetition of Figure 3.2) for L=10 km and h=5m

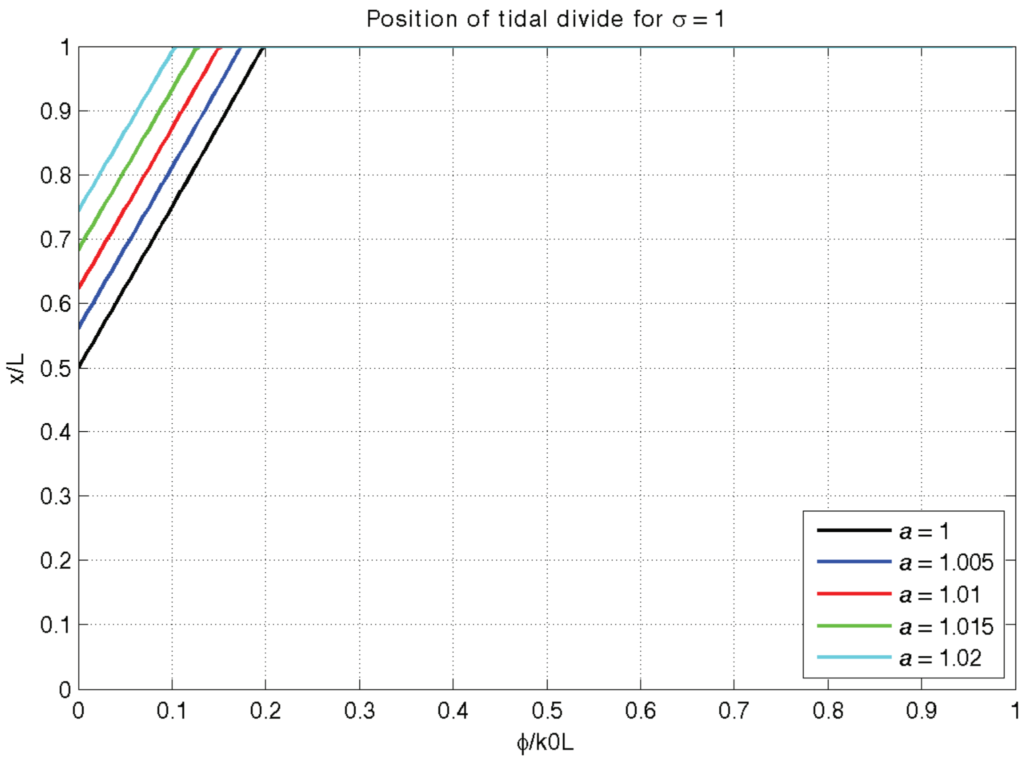


Figure 3.8 Position of the tidal divide versus the relative phase difference (φ/k_0L) for σ=1 for L=10 km and h=5m

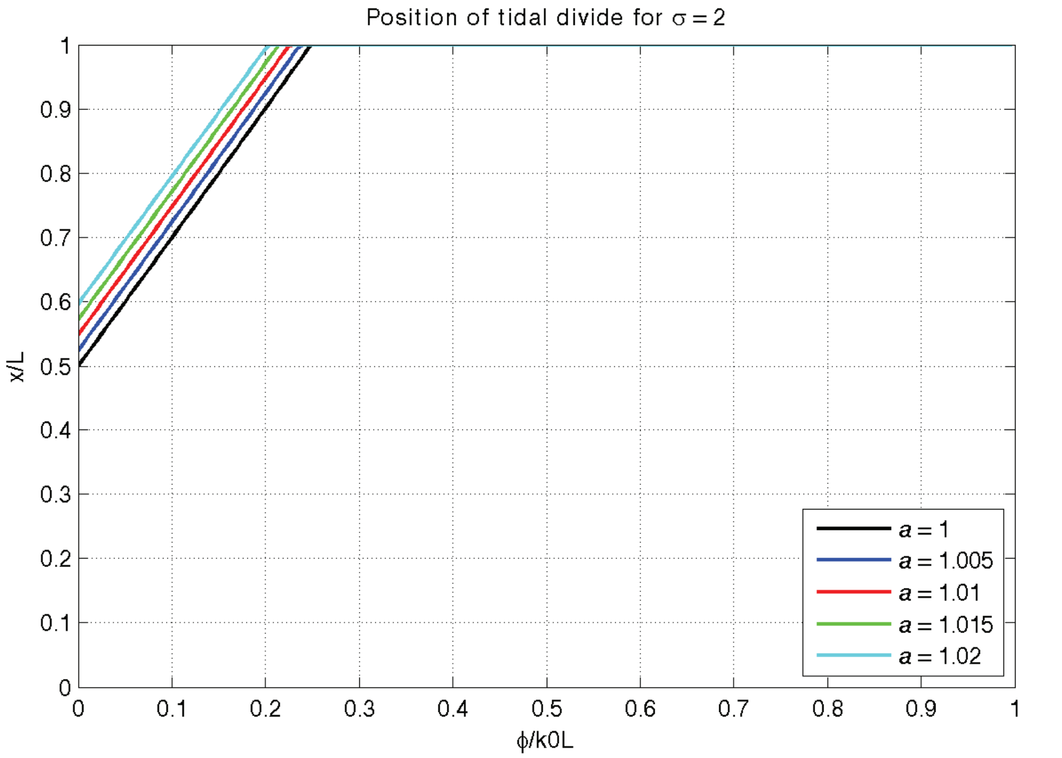


Figure 3.9 Position of the tidal divide versus the relative phase difference (φ/k_0L) for σ=2 for L=10 km and h=5m

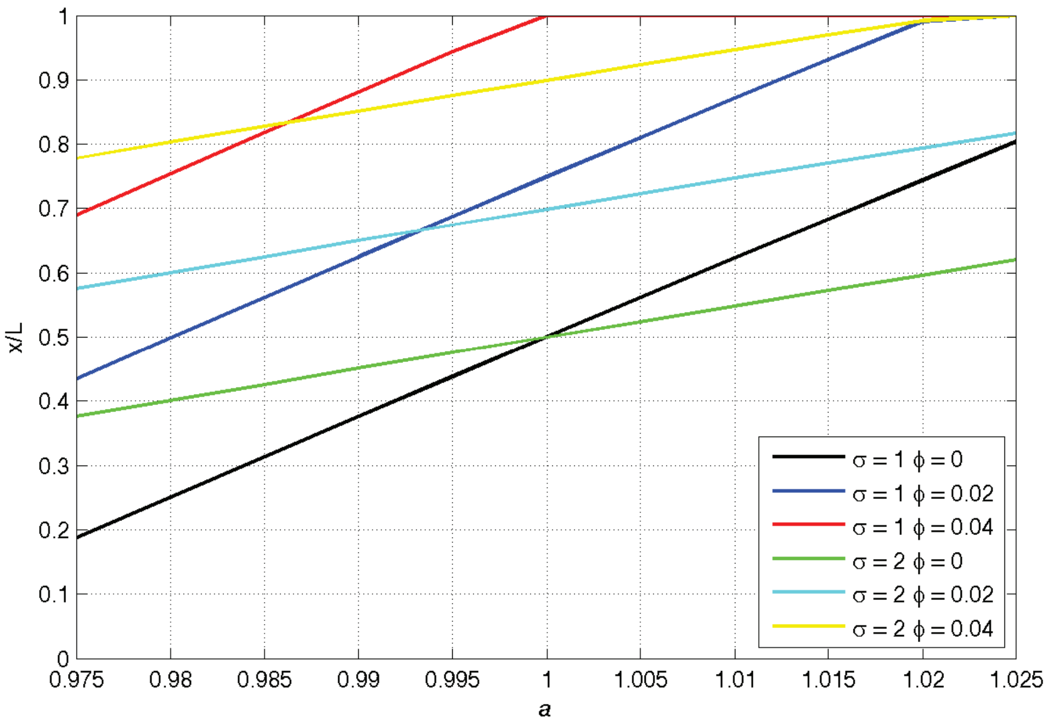
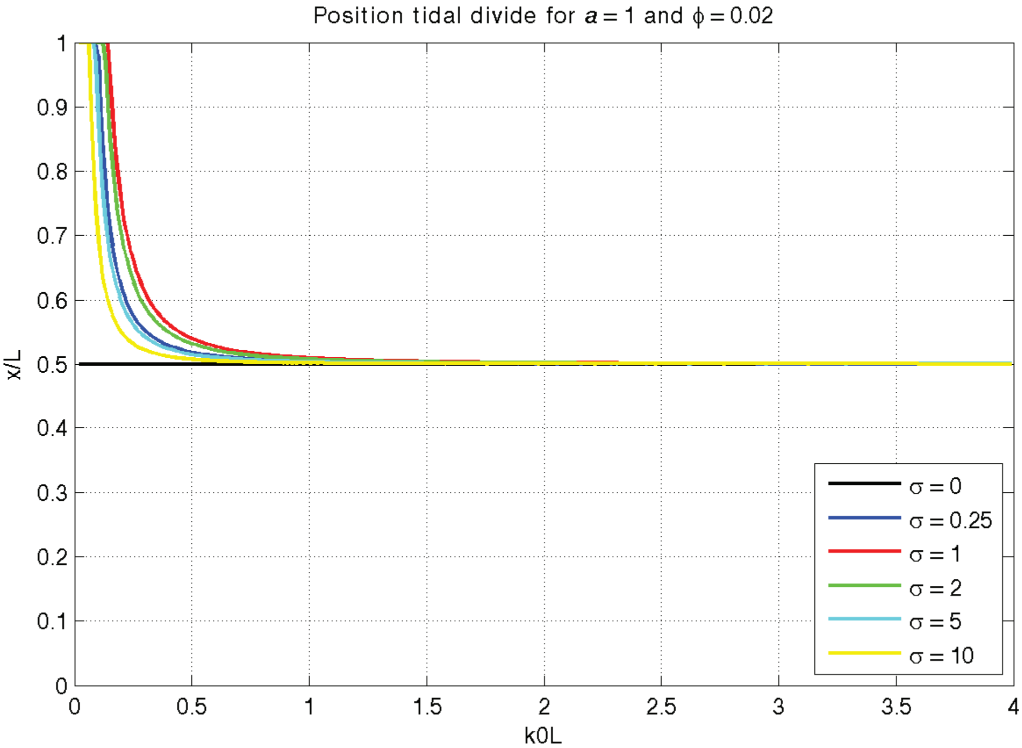
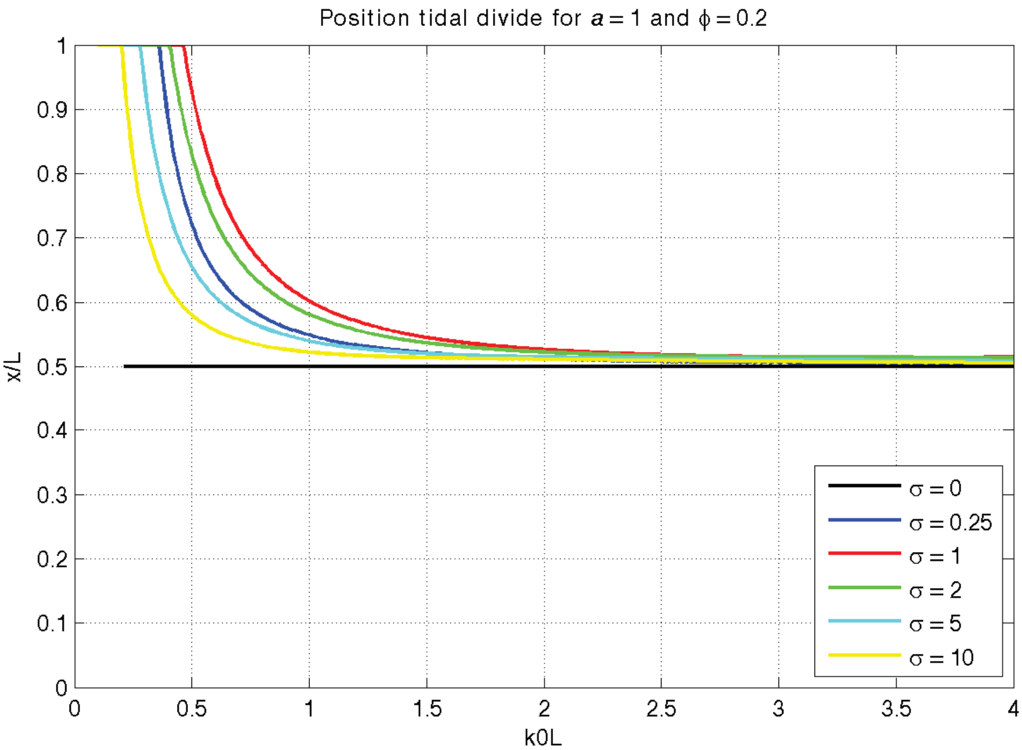
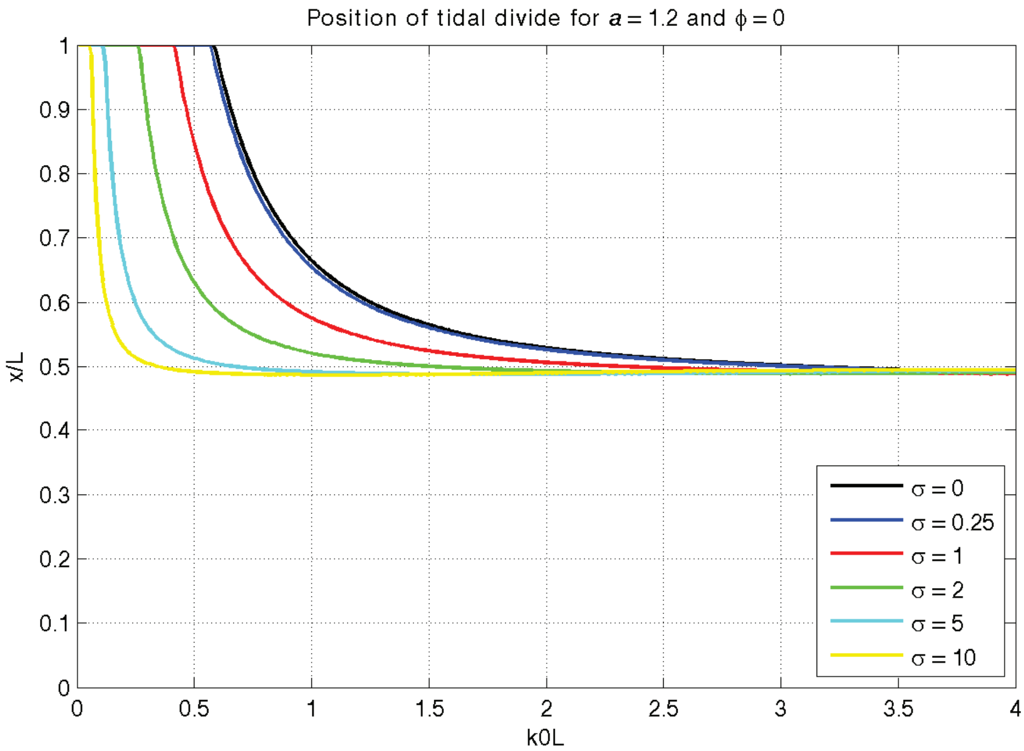


Figure 3.10 Position of the tidal divide versus the amplitude ratio for σ=1 and σ=2 for L=10 km and h=5m

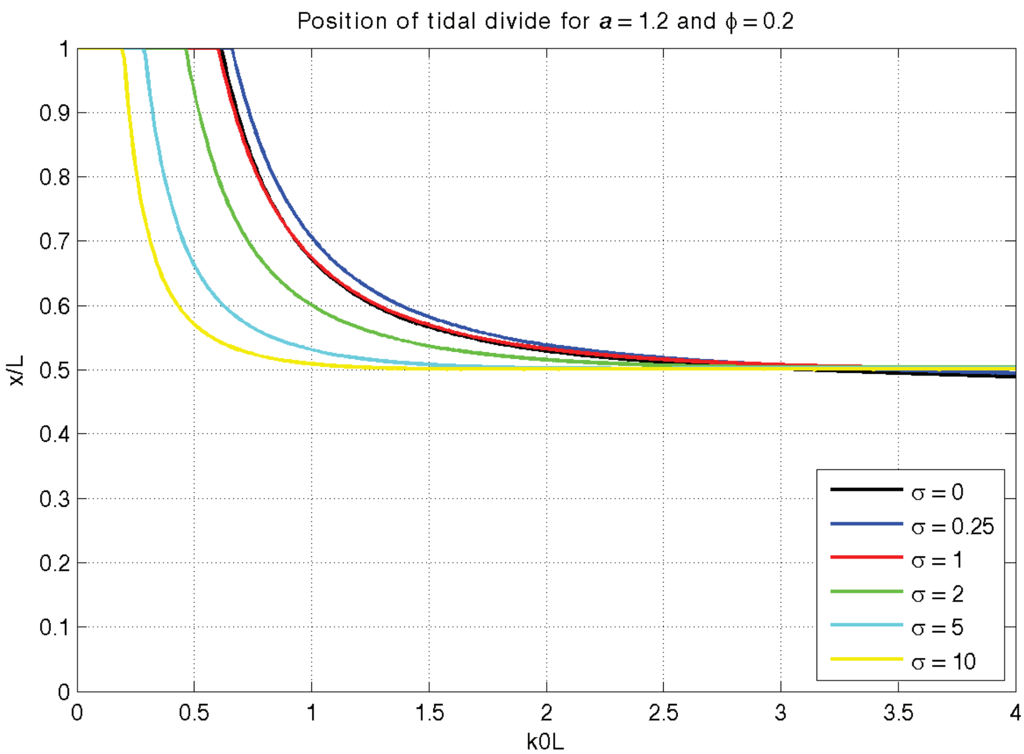
Below the effect of the amplitude ratio and phase difference for varying values of the bottom friction parameter σ is further investigated. In the figures below the position of the tidal divide is plotted against the relative channel length k_0*L for different values of the friction parameter σ.







Position of tidal divide for $a = 1.2$ and $\phi = 0$
x/L
k0L
σ = 0
σ = 0.25
σ = 1
σ = 2
σ = 5
σ = 10



Position of tidal divide for $a = 1.2$ and $\phi = 0.2$
x/L
k0L
σ = 0
σ = 0.25
σ = 1
σ = 2
σ = 5
σ = 10

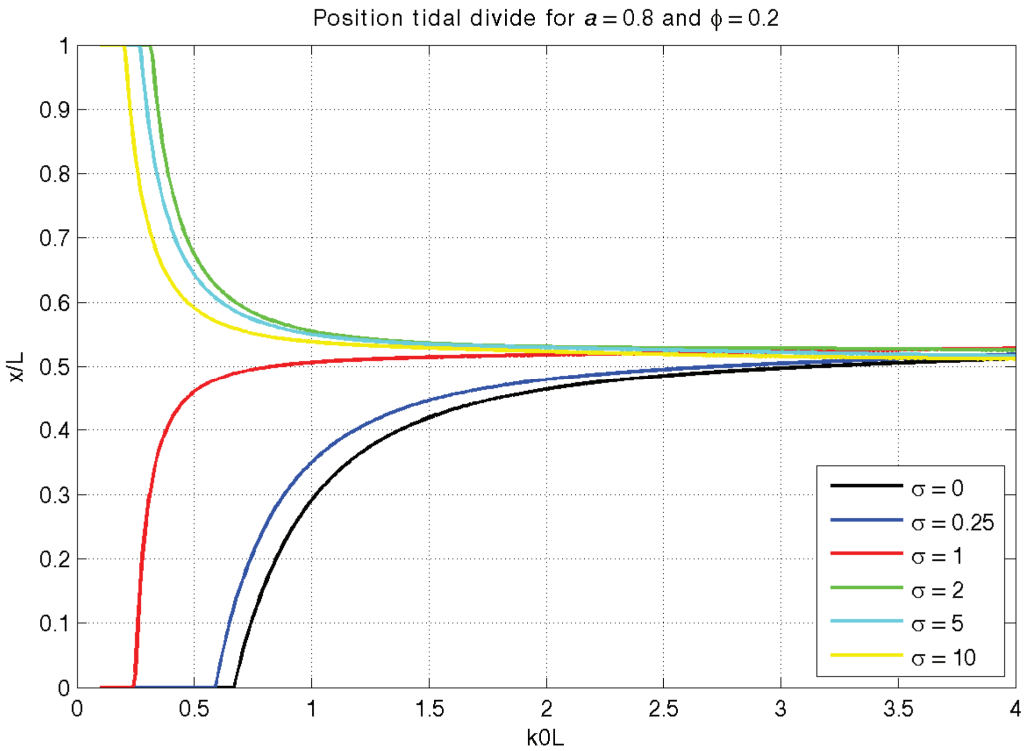


Figure 3.11a-e: The position of the tidal divide versus the relative basin length for various combination of *a* and φ, for different values of σ

The figures show that for small values of σ the position of the tidal divide shifts further towards the channel end where the wave enters last. If the friction is further increased the tidal divide shifts back to the middle of the channel. Apparently, inclusion of friction initially results in a larger influence of the phase difference. When friction becomes larger, the wave length decreases, resulting in a smaller relative phase difference. The combined effect is that the tidal divide initially moves further towards the inlet where the wave enters last and later moves back towards the middle of the channel. The configuration of *a* and φ determines for which value of σ the largest shift of the tidal divide is obtained. Figure 3.11c and e show that the amplitude ratio has less influence on the position of the tidal divide for increasing bottom friction. Figure 3.11a and b clearly show that a larger phase difference requires a larger channel length or a shorter wave length to allow for a tidal divide. In the Wadden Sea case this means that the barrier islands should have a certain length and/or the basin should be relatively shallow.

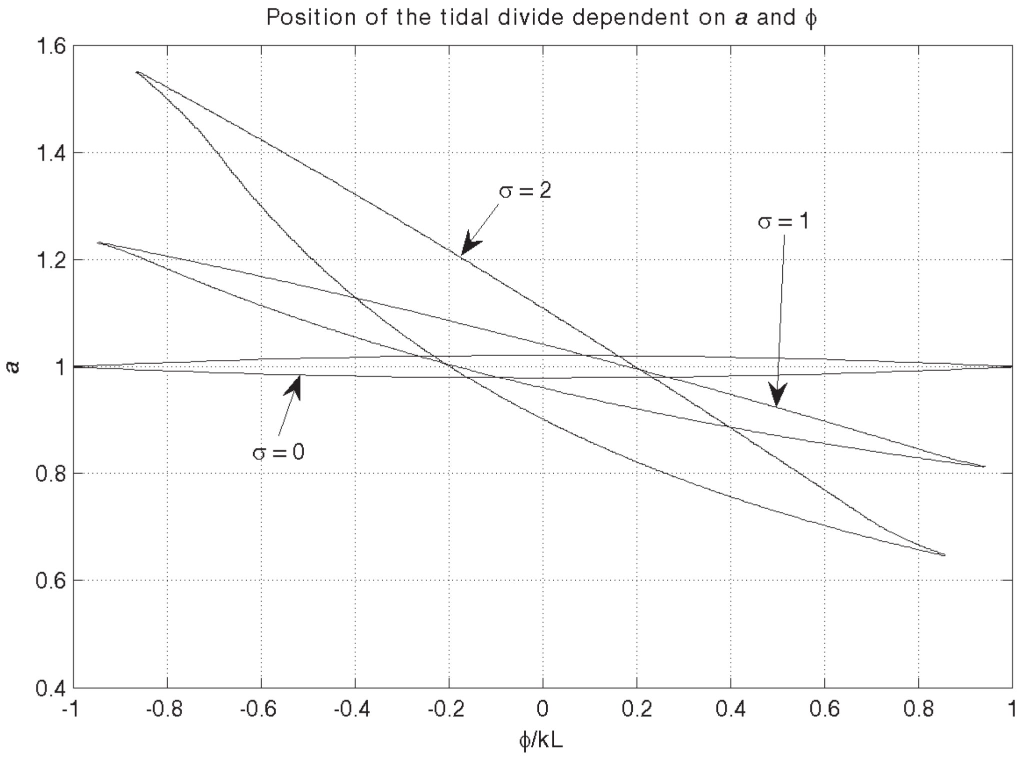


Figure 3.12 Existence of the tidal divide for *a* and φ for different values of σ (L=10km and h=5m)

Figure 3.12 shows that the condition for *a* for the existence of a tidal divide is much less strict when friction is included and the phase difference and amplitude ratio counteract each other. There are also more possibilities for the existence of a tidal divide when friction is larger. Next to this, it is remarkable that for σ>0, the condition for φ is symmetrical around zero (φ=|-φ|), but the condition for the amplitude ratio is not (*a*≠|-*a*|). This is due to the proportionality between the wave amplitude and the water depth. When *a*<1, the ratio between the wave amplitude and the water depth is smaller, generally resulting in lower flow velocities and less influence of the bottom friction and thus larger influence of and stricter condition for the amplitude ratio. This is further studied in the simulations.

3.2.3. Conclusions from the analytical approach

Before verifying the results with simulations, the most important conclusions from the analytical approach are listed:

- There is not always a tidal divide, but this is dependent on the wave amplitude, phase difference, channel length and depth and the bottom friction.

- The fact that the phase difference has a maximum in absolute sense means in the Wadden Sea case that tidal divides can only exist if there is a certain balance between the duration the tidal wave needs to propagate from the first to the second inlet at the sea side of the barrier island compared to this duration at the basin side. Hence, this is also dependent on bottom friction. This implies that the Wadden Sea (channel) must be relatively shallow or the barrier islands must be relatively long (longer channel can 'withstand' a larger phase difference).

- The tidal divide is located towards the inlet with the largest wave amplitude or the inlet where the wave enters last.

- A distinction between the case with and without bottom friction can be made. Both cases show a different sensitivity to variation of the wave amplitude ratio and phase difference.

- For the case without bottom friction, the amplitude ratio is more dominant in determining the position of the tidal divide than the phase difference. If the incoming waves have equal amplitudes, there is no influence of the phase difference on the position of the tidal divide at all. But the phase difference does have an influence on the flow velocities in this case. The phase difference has to be smaller than kL, otherwise a purely propagating wave will be present.

- For the case with linearized friction holds that: the larger the bottom friction, the smaller the effect of the wave amplitude ratio. The condition for the wave amplitude ratio is much less strict, because it has less influence of the position of the tidal divide. Inclusion of the bottom friction in first instance shows a more dominant role of the phase difference. If the friction is even larger, the effect of the phase difference becomes smaller again because the wave is dampened. Hence, the position of the tidal divide is not proportional to the value of σ.

- For the frictionless case, the phase difference becomes more dominant with increasing values of a. For the case with linearized bottom friction this coupled behaviour between a and φ is not observed.

- When friction is included and the phase difference and amplitude ratio counteract each other, the condition for a is less strict.

- With increasing channel length, the limits for the wave amplitude and phase difference are stretched. Also the absolute minimum of the amplitude of the flow velocity is decreased with increasing channel length.

- Because the bottom friction has a very large effect on the position of the tidal divide, it can certainly not be neglected. Therefore, in the following section the bottom friction parameter should be handled with care.

3.3. Simulations

The analytical approach already gave a lot of insights in the position of the hydraulic tidal divide. To arrive at the equations which have been used, some simplifications and assumptions were made. Because the wave amplitude was assumed to be much smaller than the water depth, the advective term in the momentum equation and the third term in the continuity equation were neglected. In the Wadden Sea, the amplitude of the tidal wave can be reasonable compared to the water depth, especially near the tidal divides. Therefore, also the influence of these terms should be investigated. Next to this, the friction term was linearized. The simulations will be used to see in which cases these simplifications are allowed and what the differences between the analytical approach and the simulations are. The simulations are carried out with the software packages Delft3D and Sobek[1].[2] At the end of this chapter, the software will also be used to get insight in the effects of varying geometry.

The simulations include all terms of the momentum and continuity equation. To get more insight especially in the advective term, a scale analysis can be used to reveal the relative importance of the terms in the momentum equation, see Van Rijn (1990). In the momentum equation four terms can be distinguished:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \eta}{\partial x} + c_f \frac{u|u|}{h+\eta} = 0 \qquad [3.1]$$

(1) (2) (3) (4)

By scaling them with respect to the bottom friction term, the relative importance of each term can be evaluated. The scaling factors are shown in Table 3.1.

	Term	Scaling factor	Scaling factor with $\lambda_0 = \sqrt{gh} \cdot T$
(1)	Local acceleration term	$\frac{C^2 \cdot \sqrt{h}}{g^{1.5} \cdot T \cdot Fr}$	$\frac{C^2 \cdot h}{g \cdot T \cdot u}$
(2)	Advective acceleration term	$\frac{C^2 \cdot h}{g \cdot \lambda}$	$\frac{C^2 \cdot \sqrt{h}}{g^{1.5} \cdot T}$
(3)	Water surface gradient term	$\frac{C^2 \cdot h}{g \cdot Fr^2 \cdot \lambda}$	$\frac{C^2 \cdot h^{1.5}}{\sqrt{g} \cdot u^2 \cdot T}$
(4)	Bottom friction term	1	1

Table 3.1 Four terms in momentum equation

In the table above only two new parameters are introduced, all other parameters are listed on page 25:

C Chézy coefficient [$m^{1/2}/s$]

Fr Froude number (=u/√(gh)) [-]

The length scale in the scale analysis is assumed to be equal to the frictionless tidal wave length, which is $\lambda_0 = \sqrt{gh} \cdot T$. The wave length will be affected by bottom friction, but this is not taken into

[1] Sobek River/Estuary, WL|Delft Hydraulics, November 2000. Sobek is an one-dimensional flow model, in which the momentum and continuity equation are solved numerically with the Preismann box scheme.

[2] Delft3D and Sobek can both be used to do simulations with. In the beginning Sobek was used, later on it turned out it was more practical to simulate with Delft3D. Therefore both programs have been used. The Sobek simulations are run with waves which have a frequency of $1.4 \cdot 10^{-4}$ rad/s (semidiurnal tide). Delft3D uses a 12h period, which is slightly different.

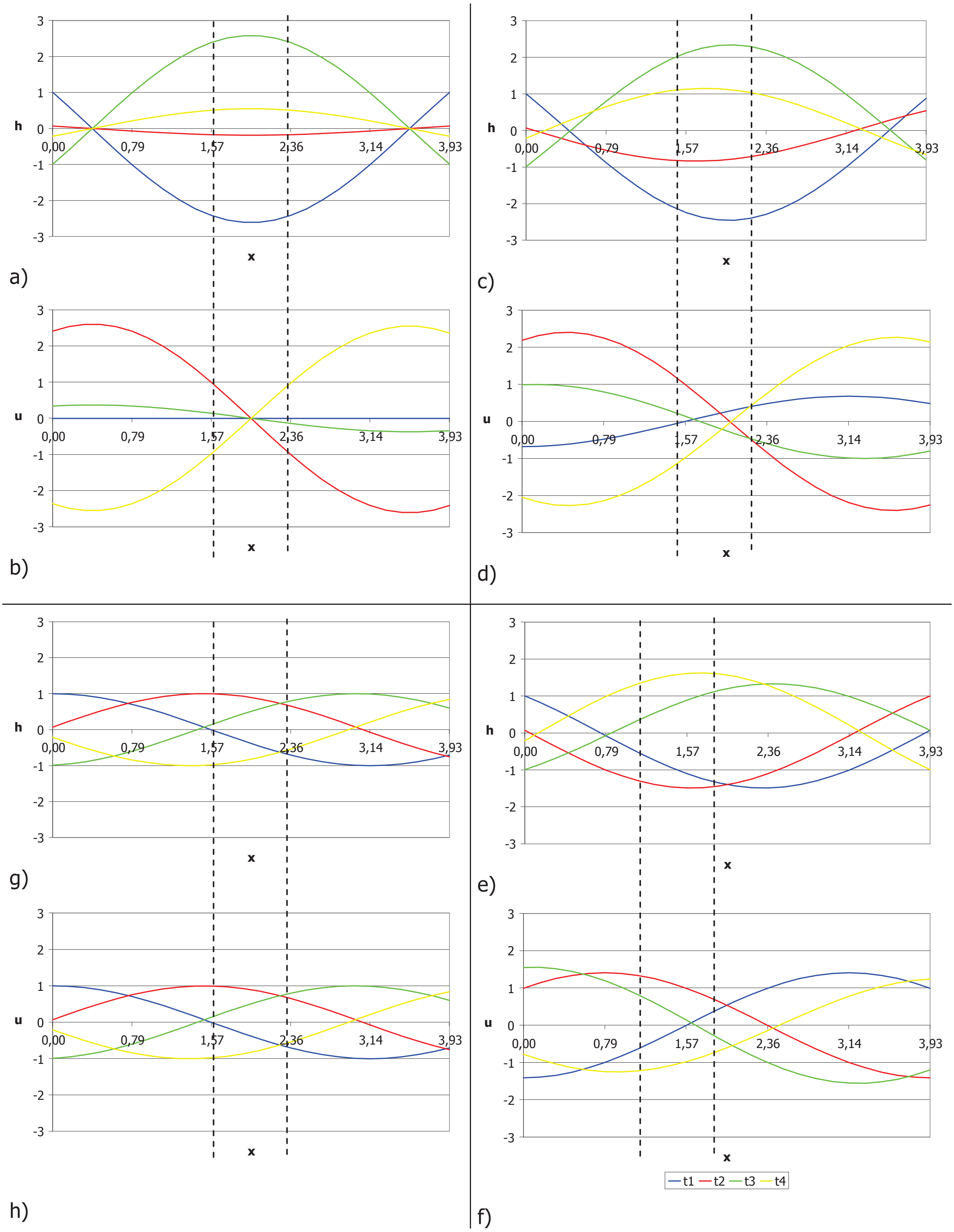


Figure 3.13 Surface elevation and flow velocity of a wave at four randomly chosen times steps in a fictitious channel, which is indicated by dotted vertical lines.

In clockwise direction starting at the left upper corner, the transition from a fully standing to a fully propagating wave is shown.

a) and b): A fully standing wave. At the antinode of the wave, the flow velocities are minimal (and in this case zero).

c) and d): A partially standing wave as a result of two propagating waves with opposite direction and a phase difference. The phase difference makes the quasi-antinode shift to the side where the wave enters last. The minimum of the flow velocities is not zero any more.

e) and f): An even larger phase difference shows a higher minimum flow velocity which is shifted even further to the side where the wave enters last, even outside the fictitious channel. In this case there would be no tidal divide in the channel.

g) and h): A purely propagating wave (flow velocities are maximal at the maximum surface elevation). There is no tidal divide.

account using the scale analysis. This introduces a small error, small enough to still give insight in the relative importance of each term. When the channel cross-section varies over the channel, the wave length can be drastically reduced and this assumption is not valid.

For all simulations a wave will occur in the channel, varying from a fully standing wave to a purely propagating wave. The variation of all parameters considered in this section, has an influence on the character of the wave (i.e. more standing or just more propagating). This is also determining the position of the tidal divide and the absolute value of the minimum of the flow velocities. Figure 3.13 on the left page illustrates this for the situation without bottom friction. This figure shows in clockwise direction the transformation of a fully standing wave to a purely propagating wave. In the Wadden Sea the tidal basins are shorter than the tidal wave length, therefore a fictitious channel is indicated with dotted vertical lines.

Note that for a standing wave the surface elevation is larger than for a propagating wave, because the waves reinforce each other. Bottom friction will have an influence on the amplitude of the wave and will also introduce a phase lag between the surface elevation and the flow velocities.

3.3.1. Bottom friction

In the analytical approach, the bottom friction was linearized. In this part the influence of the bottom friction is investigated by varying the Chézy values, see Figure 3.14. The simulations depicted in this figure were run with a water depth of 5 m, a wave amplitude at both ends of the channel of 1 m and a channel length of 10 km. Note that the Chézy value is a smoothness factor: the larger its value, the less bottom friction.

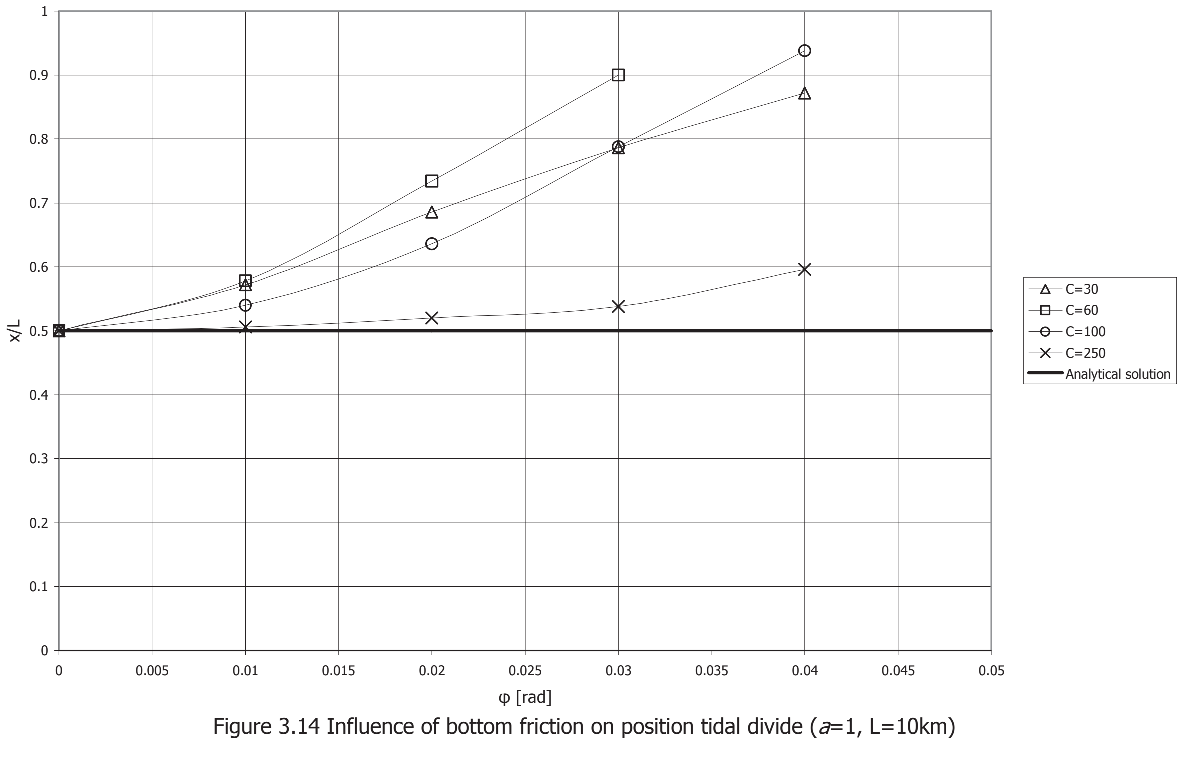


Figure 3.14 Influence of bottom friction on position tidal divide (*a*=1, L=10km)

The simulations confirm that inclusion of the bottom friction results in more influence of the phase difference and that if the roughness is high (C=30 $m^{1/2}/s$), the influence diminishes again. Of course, for a very high Chézy value, the effect of the bottom friction is negligible and the simulation approaches the analytical solution. For high roughness, the wave gets a more standing character and the relative phase difference is smaller, due to a shorter wave length. This is also illustrated by Figure 3.15, where the amplitude of the flow velocity in the channel is shown. With larger bottom friction, the flow velocities in the channel at the tidal divide are lower. The fact that the flow velocoties of the analytical solutions and the simulation with C=250 $m^{1/2}/s$ do not overlap, means that the wave amplitude of the simulations is a bit too large compared to the water depth to exactly reproduce the analytical solution.

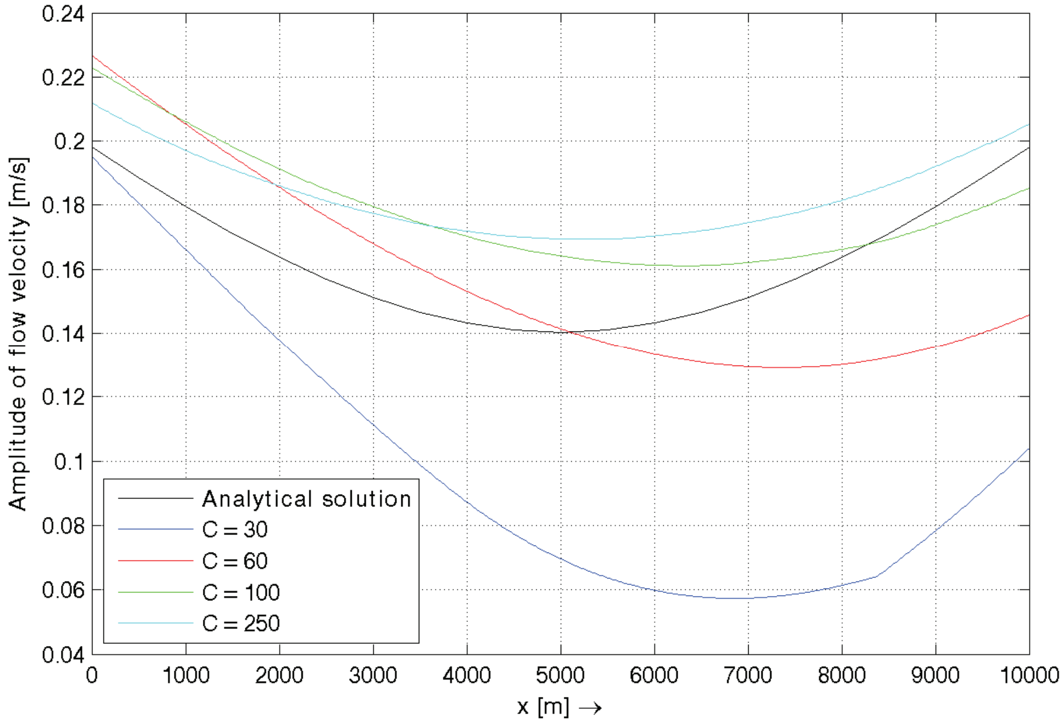


Figure 3.15 Amplitude of the flow velocity for varying roughness (a=1, φ=0.02 rad and L=10 km)

But instead of a linear effect of the phase difference, see also Figure 3.16, the lines in the simulations are curved. Probably this is the effect of the non-linearization of the bottom friction, but also the inclusion of the advective term and extra continuity term might contribute to this effect.

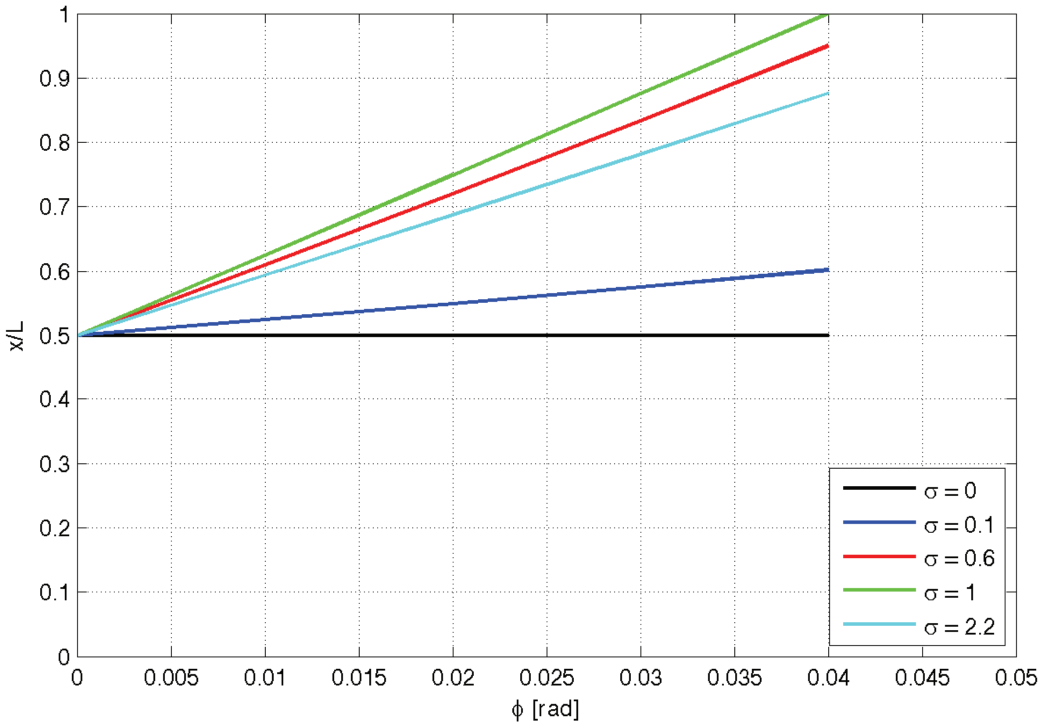


Figure 3.16 Analytical representation of position of tidal divide for a=1

The scale analysis is used to show the order of magnitude of all terms in the momentum equation for this channel configuration (h=5m and A=1m). The flow velocity which is used is the flow velocity at the tidal divide which follows from the simulation for φ=0.02, see Figure 3.15. For the length scale the frictionless wave length is used, which introduces a small error on the magnitude of term 2 and 3, which will slightly increase when the wave length decreases. With increasing Chézy value (smoother bed), all terms increase in importance with respect to the bottom friction term. The proportionality between the terms varies for each Chézy value and phase difference, resulting in another location of the tidal divide. With larger Chézy value, the water surface gradient term and local acceleration term become more dominant. Scale analysis shows that the advective term at the tidal divide is relatively small for all cases. The difference between the two figures will therefore mainly be caused by the way the bottom friction is accounted for (non-linearized).

no.	Term	C=30 $m^{1/2}/s$ u=0.06 m/s	C=60 $m^{1/2}/s$ u=0.13 m/s	C=100 $m^{1/2}/s$ u=0.16 m/s	C=250 $m^{1/2}/s$ u=0.17 m/s
1)	Local acceleration term	$O(10^0)$	$O(10^0)$	$O(10^1)$	$O(10^1)$
2)	Advective term	$O(10^{-3})$	$O(10^{-3})$	$O(10^{-2})$	$O(10^{-1})$
3)	Water surface gradient term	$O(10^1)$	$O(10^1)$	$O(10^1)$	$O(10^2)$
4)	Bottom friction term	$O(10^0)$	$O(10^0)$	$O(10^0)$	$O(10^0)$

Table 3.2 Scale analysis at the tidal divide

3.3.2. Advective term and extra continuity term

The advective term and extra continuity term, which were neglected in the analytical approach, can be neglected if the wave amplitude is small and the wave length is large compared to the water depth. The simulation for C=250 $m^{1/2}/s$ depicted in Figure 3.14 shows that the simulation approaches the case without bottom friction. This implies that for the wave amplitude - water depth configuration chosen for this simulation (A=1m and h=5m) and occurring flow velocities, the advective term and extra continuity term are small, as is also pointed out by the scale analysis. The fact that the flow velocities for negligible bottom friction (C=250 $m^{1/2}/s$) are higher than in the analytical solution, indicate that the wave amplitude is a bit too large compared to the water depth to completely neglect both terms. To further investigate the effect of the advective term and extra continuity term, the wave amplitude is varied for constant depth and a negligible friction (C=250 $m^{1/2}/s$). Also a run is made with friction (C=60 $m^{1/2}/s$). The position of the tidal divide is computed for A/h=0.5; A/h=0.2; A/h=0.1; and A/h=0.01 for a phase difference φ=0.02 rad and depth of 5m, see Figure 3.17. N.B. In this case still a channel with two incoming waves with equal amplitudes is considered. The simulations for Figure 3.17 are made with equal wave frequency and water depth.

The figure shows that a larger A/h ratio means a larger influence of the phase difference. If the wave amplitude ratio increases and the water depth is kept constant, the flow velocities in the channel also increase. From the scale analysis can be derived that the local acceleration term and the water surface gradient term are becoming less important in that case. A larger influence of the bottom friction results in a more dominant role of the phase difference, as was already concluded from the analytical solution. Probably, the advective and extra continuity term also amplify the influence of the phase difference.

In the case with negligible friction (C=250 $m^{1/2}/s$), the effect of the A/h ratio with respect to the phase difference, is becoming significant in case the wave amplitude is in the order of half the water depth. If the A/h ratio is smaller than 0.2, the advection term can be neglected, under the condition that the cross-section of the channel gradually varies over the length. In fast varying cross-sections the advection term can be of higher importance, because then the wave length can be largely decreased. If friction is included (C=60 $m^{1/2}/s$), a large influence of the bottom friction term can be noticed. The effect of the advective and extra continuity term is hard to distinguish from the bottom friction effect. If the A/h ratio is very small, the tidal divide is located more and more in the middle of the channel. In this case the wave compared to the water depth is so small that in the middle of the channel there is hardly any influence of the wave (and the flow velocities are negligible). If the ratio is increased, the phase difference has an increased influence on the position of the tidal divide. Note that these conclusions have been drawn with respect to the phase difference, the amplitude ratio is not considered.

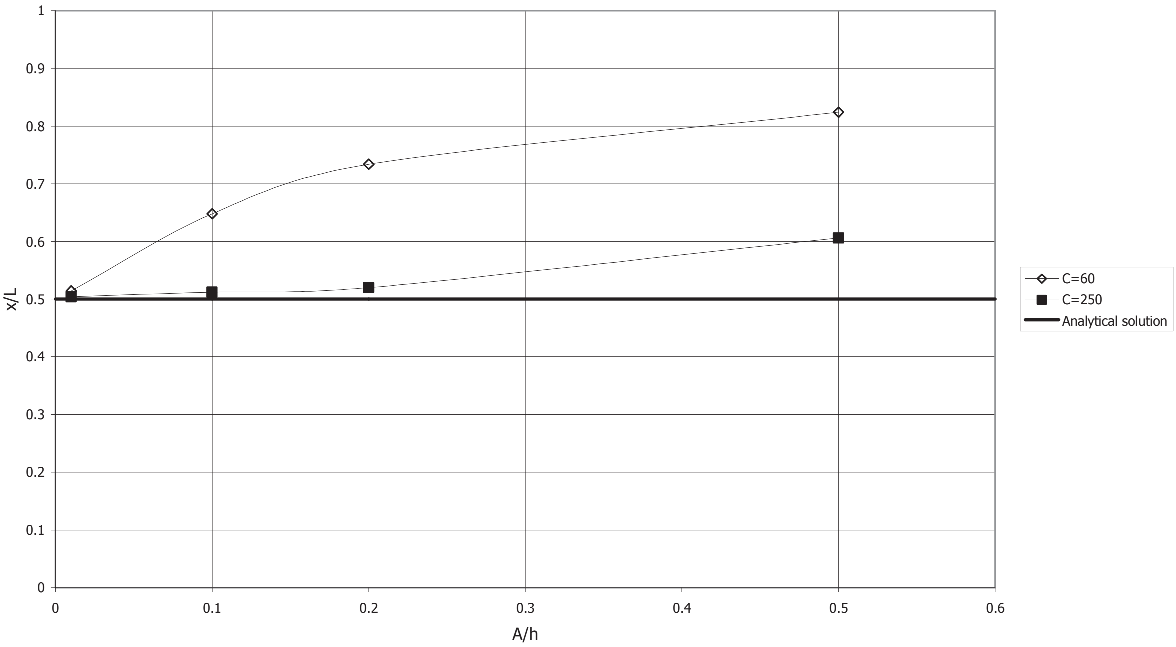


Figure 3.17 Position of the tidal divide versus the wave amplitude - water depth ratio (*a*=1, φ=0.02 rad and L=10 km)

To further investigate the contribution of all terms to the position of the tidal divide, two different cases will be studied. These cases only vary in water depth. Due to this, the case with the lower water depth in general shows higher flow velocities and thus the proportionality between the different terms in the momentum and continuity equation will be different. The following cases will be investigated:

1) A channel with a length of 10 km, a Chézy-coefficient of 60 $m^{1/2}/s$, a water depth of **5 m** and a wave amplitude in the order of 1 m.

2) A channel with a length of 10 km, a Chézy-coefficient of 60 $m^{1/2}/s$, a water depth of **2 m** and a wave amplitude in the order of 1 m.

3.3.3. Case 1: water depth of 5 m

The first case has a wave height in the order of 1 m and a water depth in the order of magnitude of 5 m. The next sections will be used to investigate the influence of phase difference and wave amplitude ratio variation.

Phase difference

The influence of the phase difference on the position of the tidal divide is already shown in Figure 3.14, see the values for C=60 $m^{1/2}/s$. The tidal divide shifts to the channel end where the wave enters last. The variation of the flow velocity over the channel is depicted in Figure 3.18. The flow velocities increase when the phase difference increases and the incoming waves have equal amplitude, because the wave gets a more propagating character. As mentioned before, the main difference between the simulation and the analytical solution is the way the bottom friction is included: linear versus non-linear.

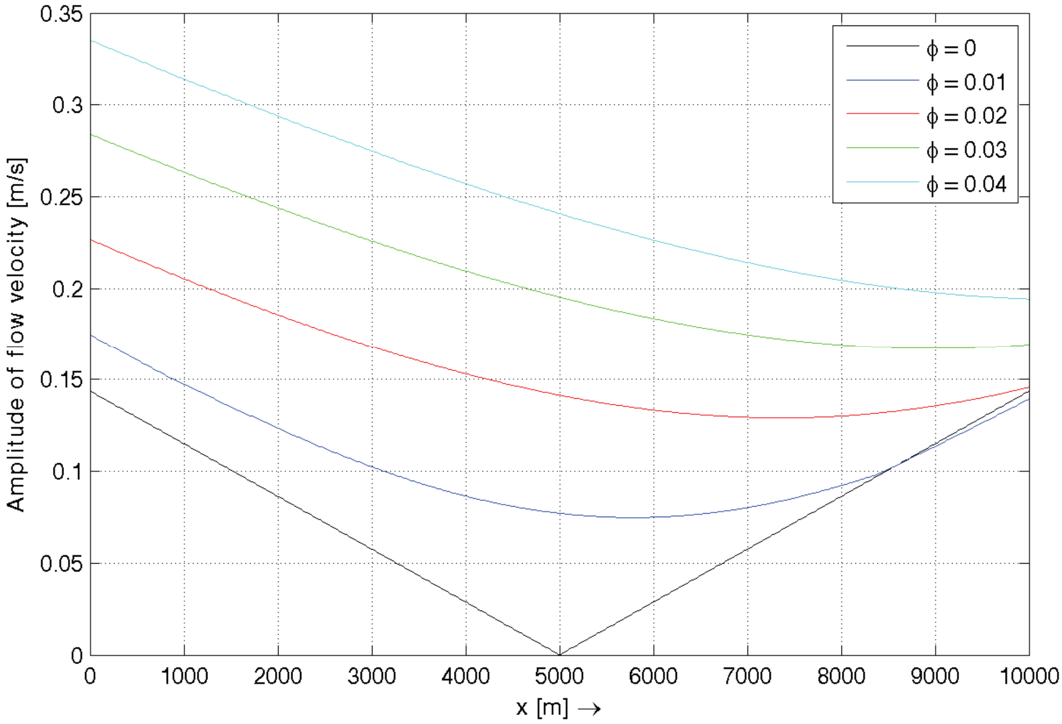


Figure 3.18 Amplitude of the flow velocity for several phase differences and equal wave amplitude (*a*=1, L=10 km)

Amplitude variation

The analytical approach showed that the tidal divide is shifted towards the channel end with the largest amplitude. Figure 3.19 shows the difference between the simulations and the analytical solution for σ=1.

From the plot it can be concluded that one value for σ does not give a good representation for all values of *a*. The value of σ is determined also by the flow velocity. In fact, for every configuration of *a* and φ, different flow velocities occur and another value of σ should be used.

When the phase difference and the amplitude ratio pull the tidal divide to the same end, the flow velocities are relatively low, see Figure 3.21. With low flow velocities, the bottom friction effect is smaller and the amplitude ratio is more important.

In Figure 3.20 the simulation for φ=0 shows that for a large amplitude ratio variation the graph flattens. This indicates that the degree to which the amplitude ratio can pull the tidal divide to a certain channel end is limited. The influence of the amplitude ratio decreases when it differs more from unity, because the flow velocities get higher and thus the bottom friction effect is stronger. There might also be a small influence of the advective and extra continuity term, but from scale analysis can be concluded that the advective term is still very small.

The simulations for *a*<1 show an increased influence of the amplitude ratio for small values of φ, see the valley in the plot of Figure 3.19. It is remarkable that for *a*<0.98, the tidal divide shifts further to the end x=0, although the phase difference is increasing and pulling the divide more towards x=L and the flow velocities are increasing as well, resulting in a more dominant role of the bottom friction and hence the phase difference. Apparently, for small values of the phase difference the amplitude ratio becomes more dominant, this results in a tidal divide pulled more towards the channel end x=0 and for larger values of the phase difference, the phase difference is dominant and pulls the tidal divide to the other end. This must be caused by the proportionality between the different terms in the equations: the non-linear terms which are included in the simulations and absent in the analytical approach and by the way the bottom friction is included (non-linearized).

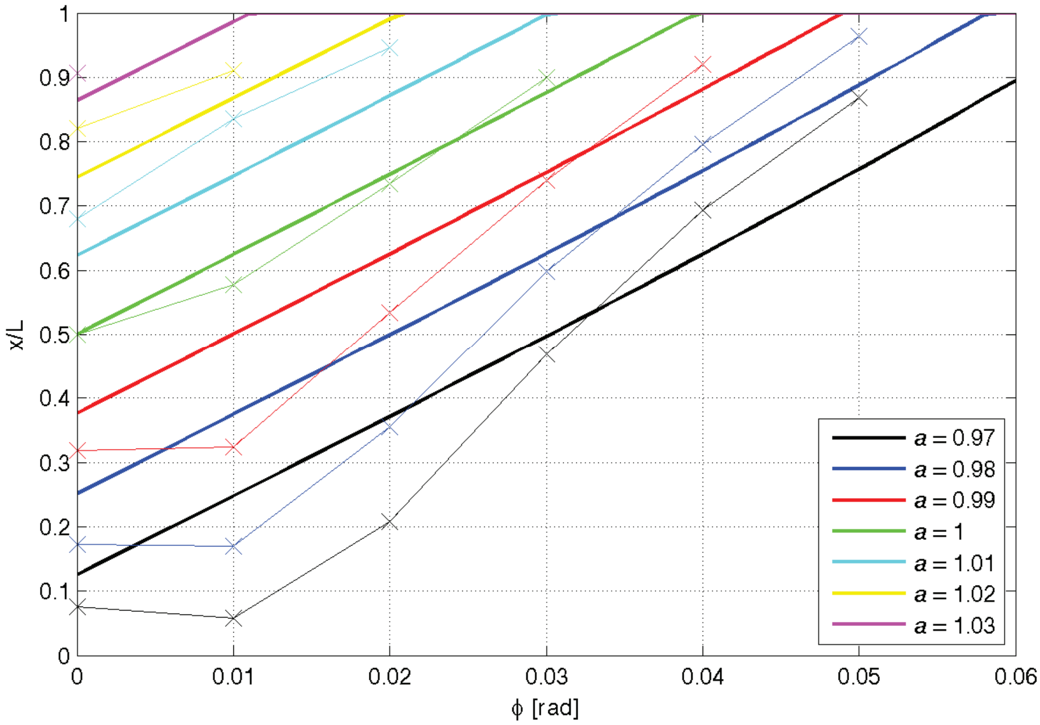


Figure 3.19 Position of the tidal divide vs. phase difference for varying wave amplitude ratio (L=10 km)
Thick lines represent the analytical solution and lines with markers represent the simulations

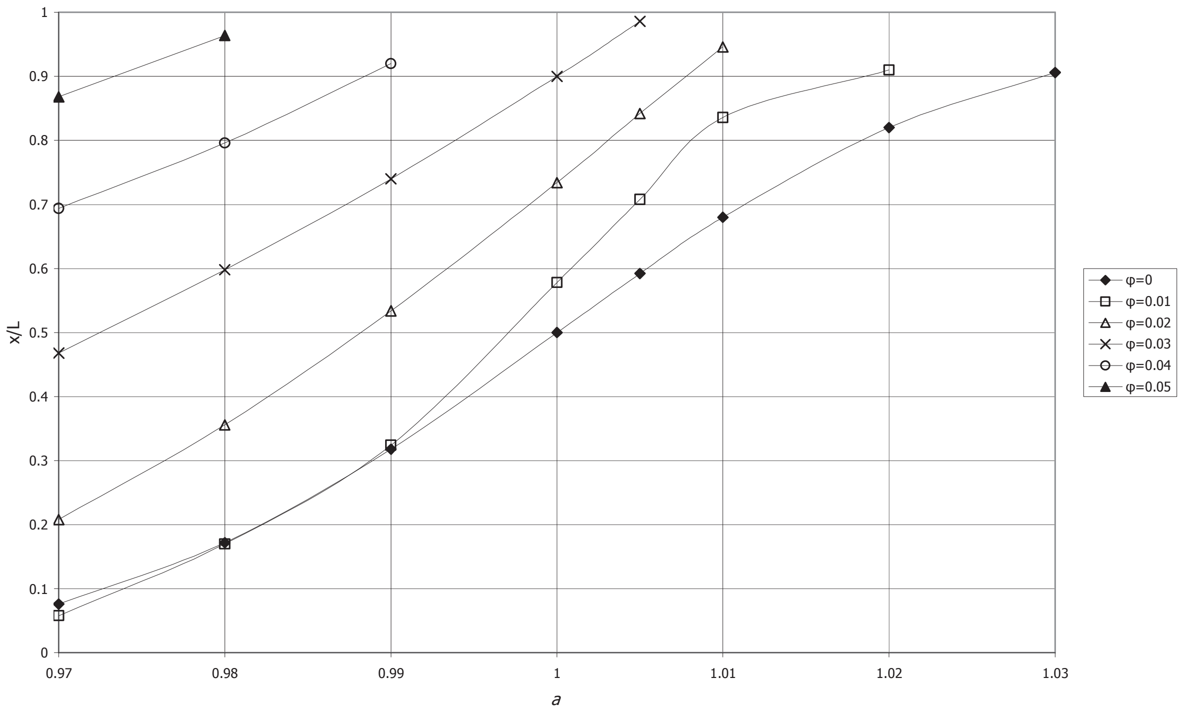


Figure 3.20 Position of the tidal divide vs. amplitude ratio for varying phase difference in rad (L=10 km)

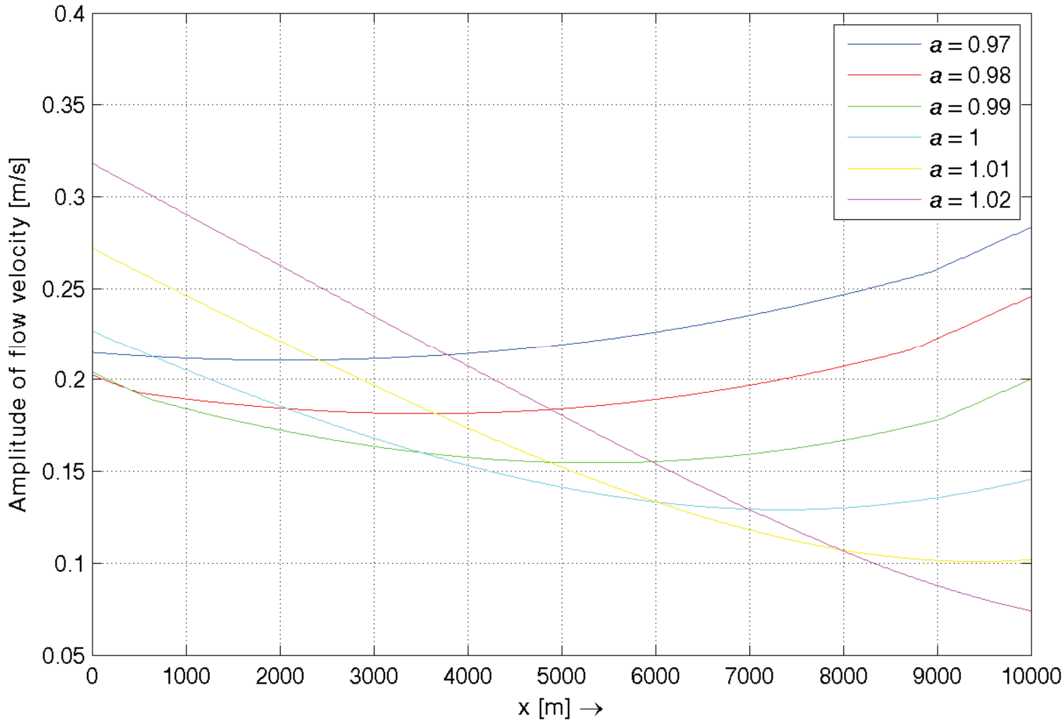


Figure 3.21 Amplitude of the flow velocity for different wave amplitudes and φ=0.02 rad (L=10 km)

Figure 3.21 shows that if the tidal divide is shifted outside the realistic domain, the flow velocities in the inlet with the largest amplitude are very low and probably this inlet will close (if morphological changes are not considered). In this way the two-inlet system might transform to a channel with a closed end (one-inlet system).

These simulations of case 1 confirm the general trends as presented by the analytical approach, where the bottom friction was linearized and advective term and extra continuity term were neglected. It also shows that the linearized bottom friction term gives a good indication of the general trends, but is also a simplification and actually has to be adapted for each case with different *a* and φ.

3.3.4. Case 2: water depth of 2 m

The lower water depth in this simulation (h=2m) results in an increase of the flow velocities. Next to this, the wave length will be smaller, because the same wave period is used. This results in an increased importance of the advective term, the extra continuity term and the bottom friction term.

Considering the amplitude ratio, it is remarkable that for case 2 the amplitude ratio has much less influence on the shift of the tidal divide, see Figure 3.22. For the same amplitude ratio, the tidal divide shifts much less. The mechanism observed for case 1 compared to the analytical approach without friction is exaggerated: the shift of the tidal divide is even less sensitive for a variation in the amplitude ratio. Due to this, the amplitude ratio can be very large.

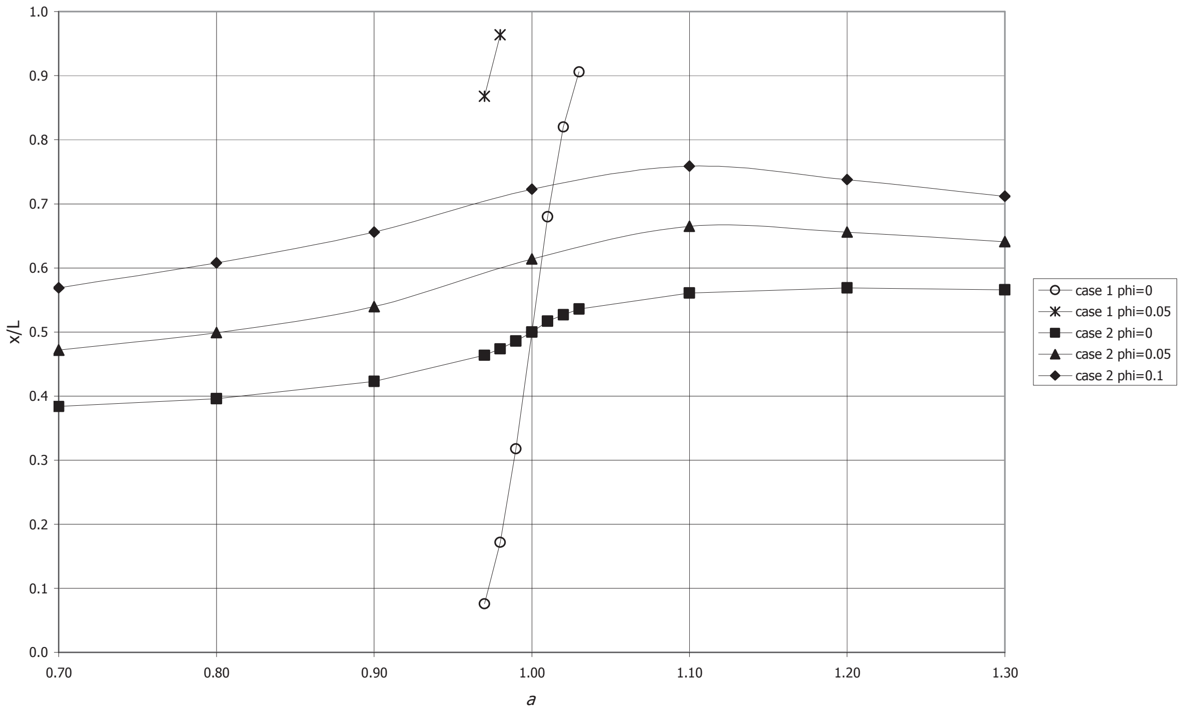


Figure 3.22 Varying wave amplitude and phase difference (in rad) for case 1 (h=5m) and 2 (h=2m)

Another remarkable effect is that with increasing amplitude ratio, the tidal divide does not necessarily have to shift further towards the end with largest amplitude. Also in case 1 the decreased influence of the amplitude ratio was observed, but the effect is now even stronger. In Figure 3.23 can be seen that the flow velocities at the tidal divide for a=1.1 are indeed very low, and the amplitude ratio can have a larger effect.

For values of the amplitude ratio *a* which are smaller than unity, the water level gradient and thus the flow velocities are smaller. This implies that bottom friction effect is smaller and the amplitude ratio is more dominant than for values of *a* which are larger than unity. Next to this, when the phase difference and amplitude ratio counteract each other, the conditions for *a* and φ are less strict to guarantee the existence of a tidal divide. Therefore the figure above is not symmetrical around *a*=1.

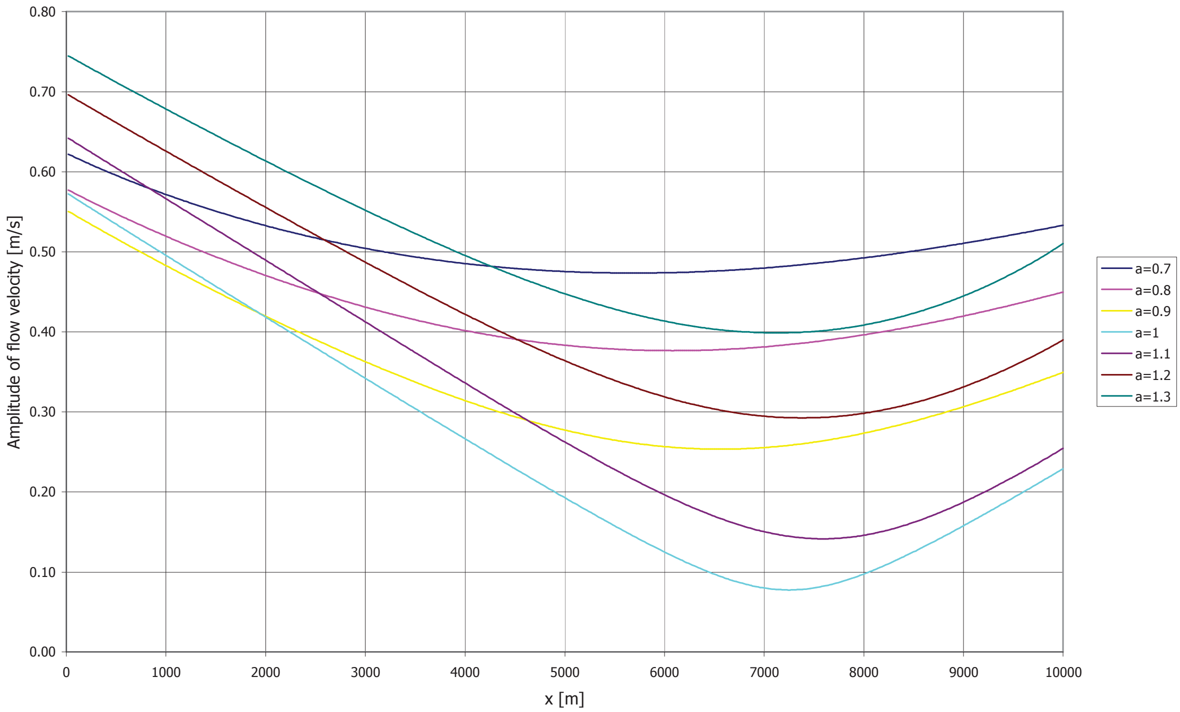


Figure 3.23 Amplitude of the flow velocity for φ=0.1 rad (case 2)

As a comparison the analytical approach is used again. Figure 3.22 and Figure 3.24 can be compared. The value of σ is chosen such, that the simulations are resembled best. The lines are slightly curved, but do not show the decreased influence of the amplitude variation for the largest values of *a*. This effect is thus introduced by the non-linearized bottom friction, the advective term and/or the extra continuity term.

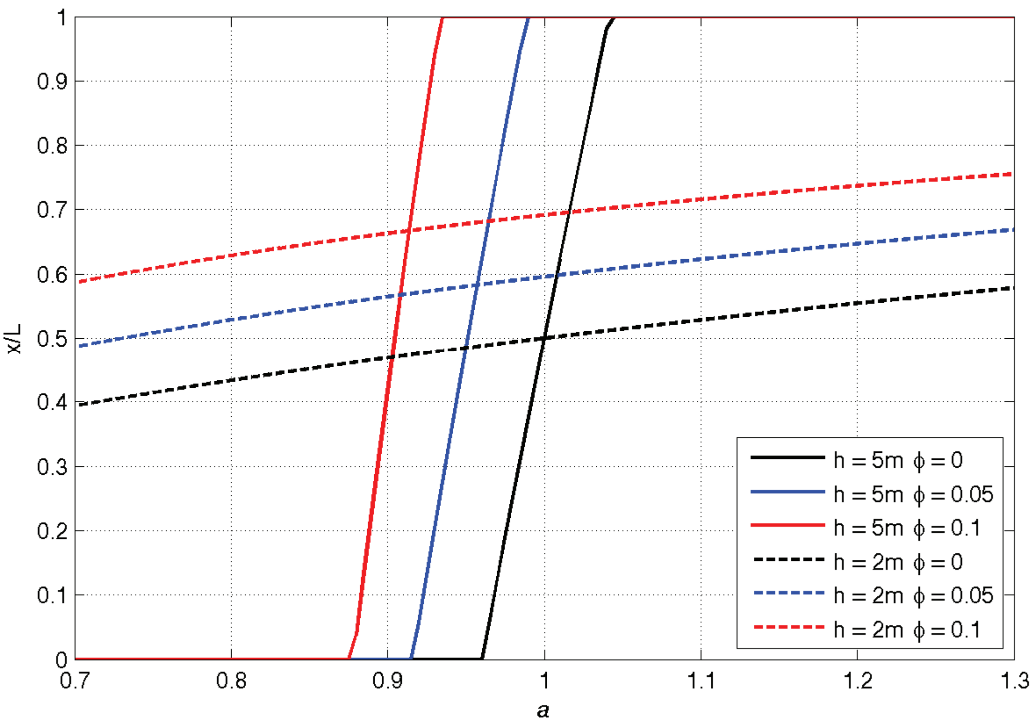


Figure 3.24 Analytical solution for Figure 3.22, cases with h=5m with σ=1 and with h=2m with σ=5

The simulations are used to verify the observations from the analytical approach. The following conclusions can be drawn:

- The simulations confirm all conclusions from the analytical approach.

- The depth of the channel is an important parameter, because it determines to what degree the waves 'feel' the bottom and thus the importance of the bottom friction. Next to this, a small water depth in combination with a relatively large wave amplitude results in large flow velocities and thus also more influence of the advective and extra continuity term.

- When considering a case with a relatively small wave amplitude compared to the water depth (A=1m and h=5m), both the amplitude variation and the phase difference are important for the position of the tidal divide. If the water depth is decreased to 2 m, the advective, continuity and bottom friction term become more important, and due to this the phase difference gains more influence on the position of the tidal divide. The amplitude ratio is mainly affecting the magnitude of the flow velocity and has minor contribution to the position of the tidal divide.

- The configuration of *a* and φ also influences the flow velocities in the channel. Due to this the importance of all terms in the momentum and continuity equation are affected. An example is the simulation with increasing wave amplitude ratio, where its own influence was decreased and the wave amplitude ratio eliminated itself. In this way, the behaviour between *a* and φ is coupled again, as was also observed in the case without friction.

- The case with linearized bottom friction showed that for higher values of σ, the friction is so large that the phase difference can be larger again before leaving the realistic domain. Hence more bottom friction does not automatically mean a larger influence of the phase difference. This is confirmed by the simulations with varying Chézy values. The non-linearized bottom friction in the simulations show a more varying influence of the bottom friction. This is due to the fact that the flow velocities determine the value of σ and actually σ has to be found by iteration. In the graphs this is visualized by curved instead of straight lines.

- In the Wadden Sea, the waves are very long compared to the water depth, but the tidal range can also be considerable. At the tidal divides, the flats even fall dry. This implies that the bottom friction, advective and extra continuity term definitely have to be included in the simulations.

3.3.5. Geometry variation

Also a varying geometry can introduce non-linear effects. In this section the influence of different geometries is briefly studied for the channel with a depth of 5m and a Chézy coefficient of 60 $m^{1/2}/s$.

Influence of channel length

The influence of the channel length was already briefly described with the analytical approach. If the channel length is doubled, the phase difference can be more than quadrupled. The results here are not very different from the analytical solution, except that friction is not linear.

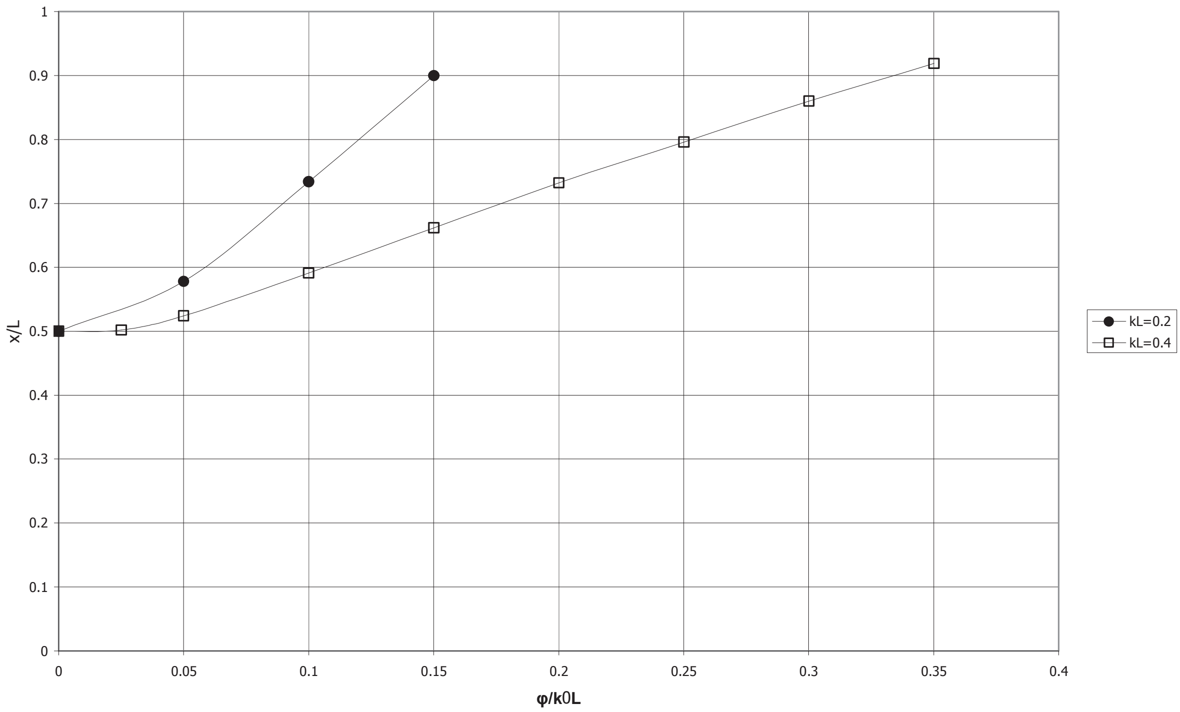


Figure 3.25 Influence of channel length for a=1

Depth variation
To investigate the influence of depth variation, four cases are considered, see Figure 3.26. The results of the simulations are plotted in Figure 3.27. The shape of the wave is not significantly affected by the depth variation, which means that the nodes and antinodes of the wave will be located more or less at the same positions as with a constant depth. Therefore the depth will influence the flow velocities only by changing the wet cross-section at each location. The tidal divide will be located at the location were the wet cross-section is largest. In Figure 3.26 the (upper part of the) wave envelop of the wave resulting from two incoming wave with a small phase difference is indicated with a gray dotted line. The influence of the depth configurations on the position of the tidal divide can now be seen in the figure, by imagining the place where the wet cross-section has a maximum (water depth is the largest).

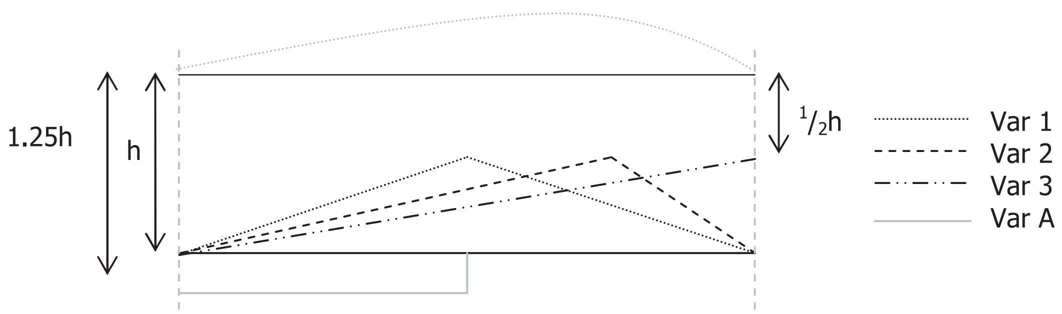


Figure 3.26 Depth configurations

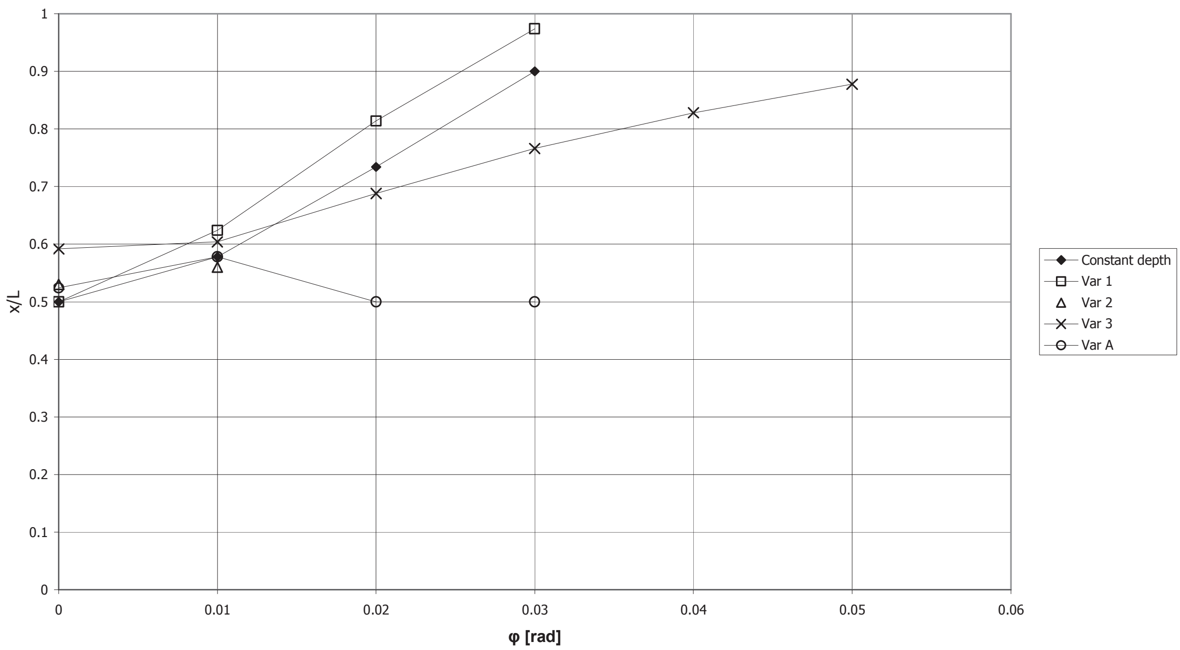


Figure 3.27 Position of tidal divide vs. phase difference for various depth configurations (a=1 and L=10 km)

Width variation

If the channel systems of the Wadden Sea are schematized to one-dimensional channel sections (fractional structures), the summation of the widths of all branches shows a total width which increases from the inlet to the basin boundary (tidal divide), see Figure 3.28. Figure 3.29 shows a simplification of this effect, in which the width is linearly increasing from the inlet to the middle of the channel and the depth is taken constant.

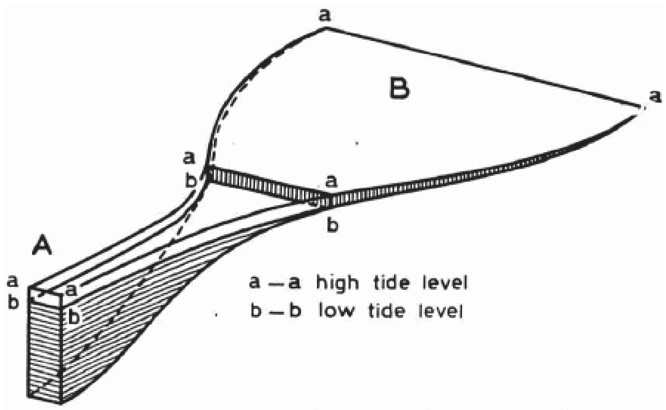


Figure 3.28 Basin schematisation (van Straaten and Kuenen, 1957)

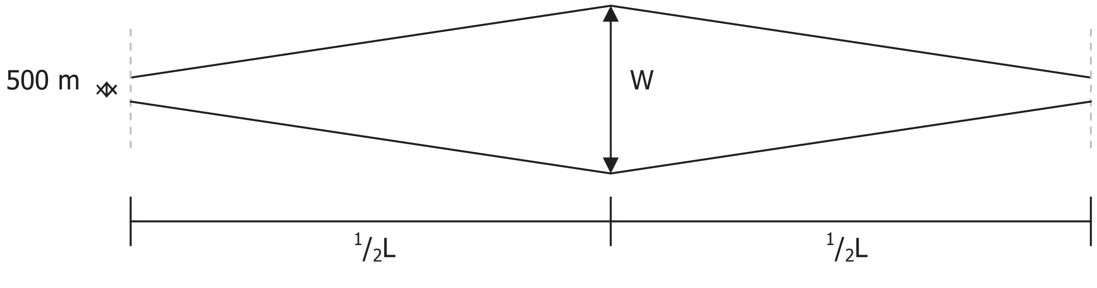


Figure 3.29 Width configuration

With increasing width the same mechanism plays a role as with depth variation: the flow velocities are minimal at the location where the wet cross-section of the wave is largest, in this case at x=½L. One would expect the wave amplitude to decrease if the channel is getting wider, but the opposite occurs, as is illustrated by Figure 3.30. This implies that the wave gets a more standing character due to the widening of the channel: the waves reinforce each other. At the boundary conditions, the surface elevation is imposed and can not increase. This results in relatively high velocities at the inlets, which rapidly decrease.

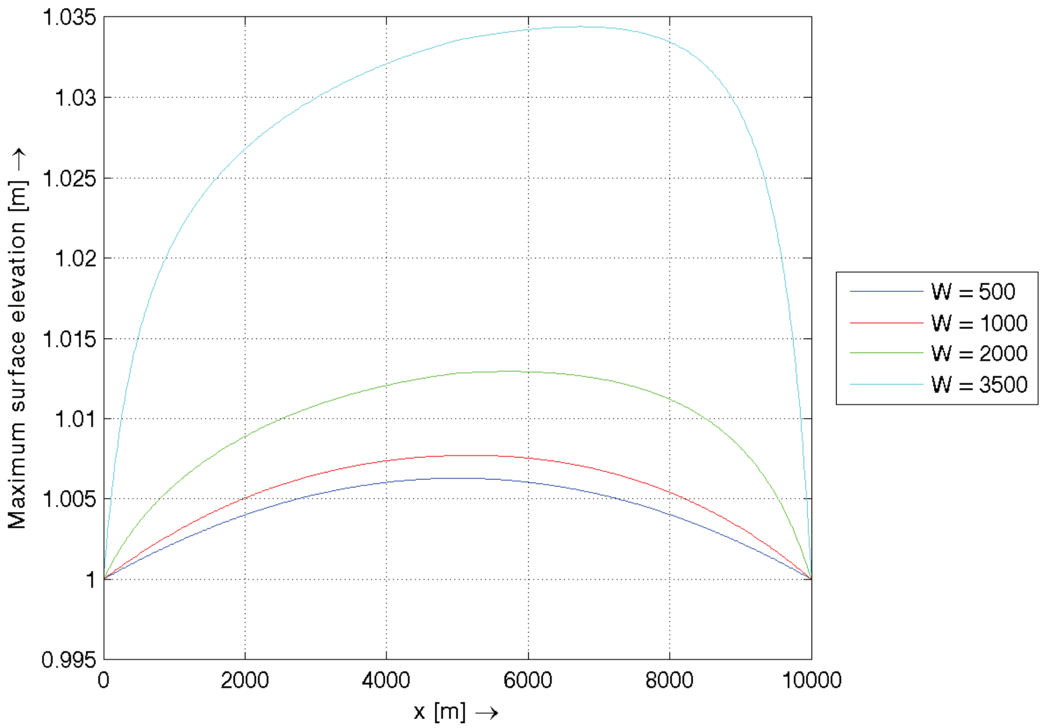


Figure 3.30 Maximum surface elevation for different maximum widths at x=$^1/_2$L, for *a*=1 and φ=0.02 rad

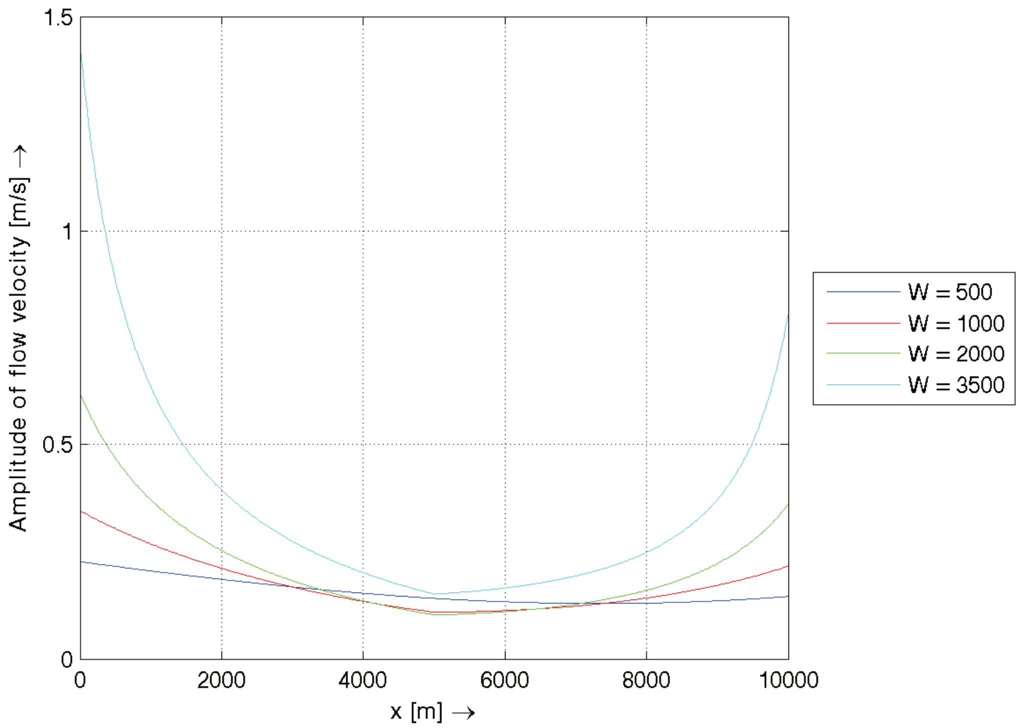


Figure 3.31 Amplitude of the flow velocity for different maximum widths at x=$^1/_2$L, for *a*=1 and φ=0.02 rad

If a morphological development is coupled to this behaviour, this would mean that the inlets will deepen if the basin gets wider. This results in a basin geometry as illustrated by van Straaten and Kuenen (1957), see Figure 3.28. The effect of increased tidal range in the back of the basins is also observed in the Wadden Sea. In the Wadden Sea, the cumulative channel width as schematized in Figure 3.28 is a result of the location of the tidal divide. Therefore, the branching of the channel system helps to keep the tidal divide at its location.

Conclusions regarding the basin geometry:

- Depth and width variations influence the position of the tidal divide by changing the wet cross-section of the channel, and in this way the flow velocities. For increasing channel width, as is the case in the Wadden Sea, the tidal range increases towards the middle of the channel, keeping the tidal divide at its position.

- The channel length determines the space the wave has to move inside the channel. The antinode of the wave (where the flow velocities are minimal, i.e. the tidal divide is located) can shift further before leaving the channel when the channel is longer.

- More research has to be done to investigate the combined effect of changing width and depth. Next to this, the amplitude variation should also be studied for varying cross-section, as well as varying cross-section for more non-linear cases (h=2m).

3.4. Final conclusions

Now the most important conclusions of this chapter are summarized and repeated.

- There is not always a tidal divide, but this is dependent on the wave amplitude, phase difference and basin geometry. A tidal divide can exist if a (partially) standing wave occurs in the channel.

- Generally, the tidal divide is located towards the inlet with the largest tidal range or to the inlet where the wave enters last.

- A distinction between two extreme cases can be made:
    - A case with a very low wave amplitude compared to the water depth, in which the flow velocities are very low and the advective, extra continuity and bottom friction term can be neglected.
    - A case with higher wave amplitude and flow velocities in which the advective, extra continuity and bottom friction term have to be included in the simulations.

- When bottom friction becomes more dominant, the phase difference is more important in determining the position of the tidal divide and the influence of the amplitude ratio limited. Further increasing bottom friction can also dampen out this effect again and move the tidal divide back towards the middle of the channel.

- In the idealized case without friction and advective and extra continuity term, the amplitude ratio is much more important than the phase difference. When the incoming waves have equal wave amplitude, the effect of the phase difference is even nil.

- The configuration of the wave amplitude ratio and phase difference is affecting the flow velocities in the channel. This influences also the importance of the non-linear terms (bottom friction, advective and extra continuity term). When the amplitude ratio and phase difference counteract each other, the conditions of these parameters for the existence of a tidal divide are less strict.

- The depth is an important parameter, because it determines the magnitude of the flow velocities in the channel, as well as the degree to which the waves ‘feel’ the bottom and the importance of the bottom friction.

- Increasing channel length results in less strict conditions for the wave amplitude ratio and phase difference.

- The widening of the channel results in a more standing character of the wave, with corresponding higher surface elevation and lower flow velocities. Due to this, the increasing width of the channel more or less keeps the tidal divide at its place.

- The effect of the basin geometry on the position of the tidal divide needs to be further investigated in order to be able to draw more specific conclusions.

4. Definition of the tidal divide

In the previous chapter the simplified case is considered to get insight in the parameters determining the position of a hydraulic tidal divide. Now the step is made to the complex situation of the Wadden Sea, which includes a more realistic tidal wave, consisting of dozens of tidal components, and a more realistic bathymetry. With a Delft3D model of the Wadden Sea, water levels and flow velocities can be calculated. With these data different definitions of a hydraulic tidal divide are analyzed. The morphological tidal divide is defined by using the 'vaklodingen' data of Rijkswaterstaat, which have a higher resolution than the Delft3D bed level schematizations.

4.1. Hydraulic tidal divide

As mentioned before, a distinction is made between hydraulic and morphological tidal divides. The question 'what is a hydraulic tidal divide?' is still not properly answered. The most obvious definition is that a hydraulic tidal divide is a location where the flow velocities are minimal. In principal this minimum is not a clear line, as it was in the channel schematization, but a cloud. By using the hydraulic tidal divide as a criterion for the boundary between adjacent basins, a line is desired. How can this line then easy be determined? And, is there always a hydraulic tidal divide between basins, or are there situations imaginable in which the flow velocities are so large that it no longer makes sense to point out a hydraulic tidal divide? For example when the flow exchange between the basins is very large and the basins do not operate autonomously, as is the case between Marsdiep and Vlie. However, determination of the equilibrium of basins requires basin surface areas as input and in this way a boundary between the basins. When this boundary is defined by a (hydraulic) tidal divide, then there should always be a location where this line can best be drawn.

But, hydraulic tidal divides can also exist at locations where there is definitely no basin boundary. For example at a flat which is drained by two channels at either side of it, there the hydraulic tidal divide splits the flat in two catchment areas. That not every hydraulic tidal divide is a basin boundary has to be kept in mind by analyzing hydraulic tidal divides in the Wadden Sea.

Going back to the question how to determine the position of a hydraulic tidal divide, multiple options can be considered. For example the location where the flow velocity is minimal, or the location where the residual flow is minimal, which indicates the amount of exchange of water between the basins, or the location where the tidal prism is minimal. The age of water, i.e. the time it takes to refresh the water mass at a certain location, or lines with the same water level can also be used. In this chapter a couple of options for the definition of the hydraulic tidal divide are investigated with the goal to come up with a clear definition. When a definition gives multiple options to draw a line, at least the bandwidth of these options is as small as possible. In the next sections will become clear why it is so hard to define a line and why at lot of definitions are arbitrarily. First, the model which is used to execute the flow simulations is briefly described.

4.1.1. Delft3D model

With the software package Delft3D the hydrodynamics in the Wadden Sea are modelled. Only tidal forcing is considered for two spring-neap tidal cycles (one month) for the bathymetry of 2006[3], see Figure 4.1. With this simulation, the possible definitions for the hydraulic tidal divide are studied.

[3] The bathymetry of 2006 consists of measuring data of the period 1999-2006.

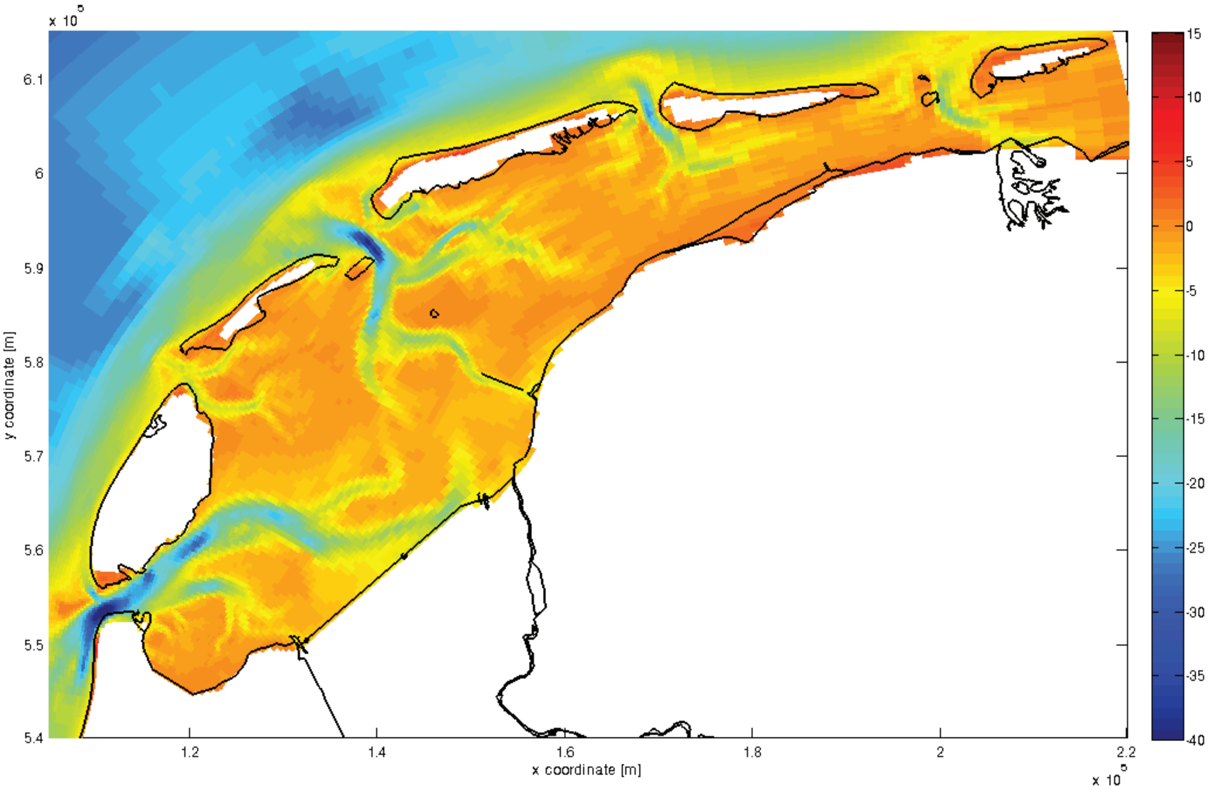


Figure 4.1 Bathymetry of 2006 as modelled in Delft3D

The tidal divide behind Schiermonnikoog is not considered because it is located too close to the model boundary (2-3 grid cells). The tidal divides behind Ameland and Terschelling are modelled less accurate because in m-direction (=island parallel) the grid is rather coarse here. This results in relatively large jumps in the lines representing the hydraulic tidal divide.

The model settings are summarized in appendix A.

4.1.2. Possible definitions

In this section multiple definitions are considered and compared. At the end, a definition will be chosen to execute the analysis of the movement of hydraulic tidal divides.

Amplitude of the flow velocity

For the simplified case, it was easy to determine the position of the tidal divide, because there was a clear minimum in the flow velocity. If the same technique is applied to the Wadden Sea, the maximum flow velocity has to be determined for each grid cell, see Figure 4.2. The figure indicates the hydraulic tidal divide by the darker blue colours. To define a more exact position, the minima in m-direction (island parallel direction) are plotted in Figure 4.3. It clearly shows that there are multiple possibilities to draw a line and that this figure gives no definite answer.

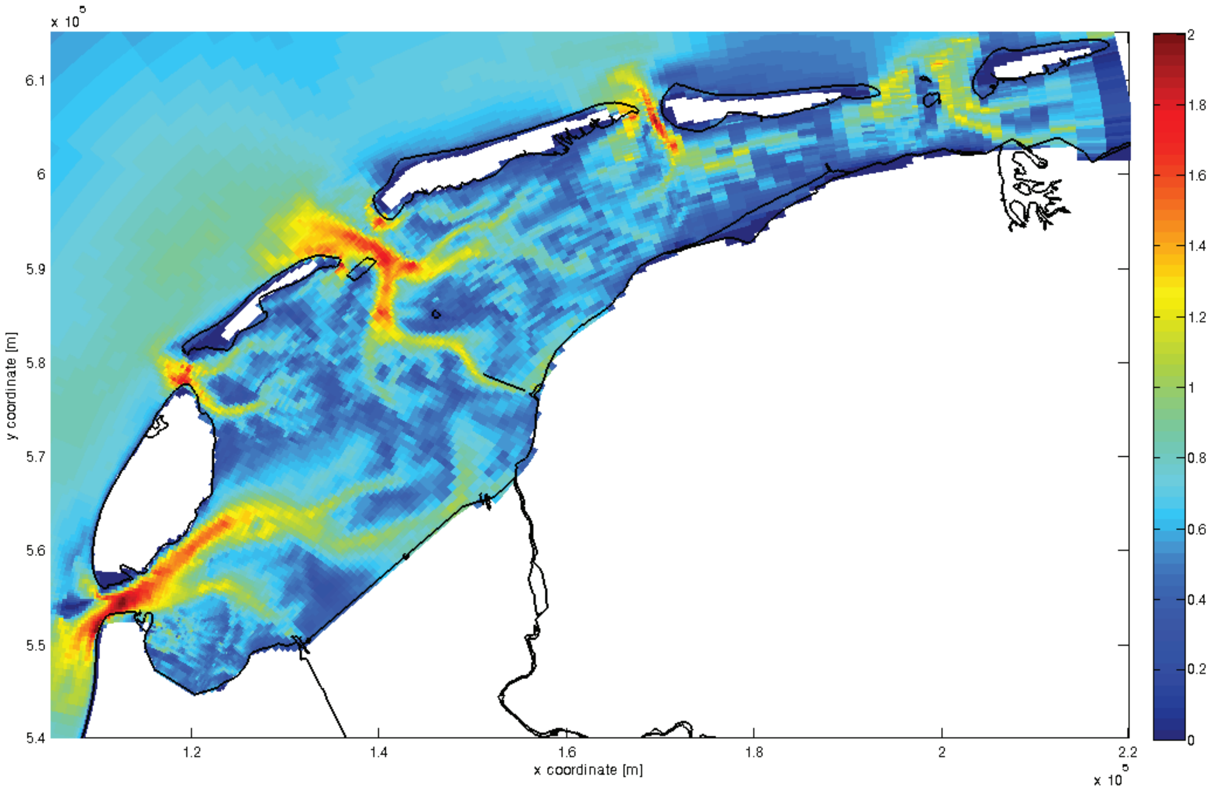


Figure 4.2 Maximum velocity for each grid cell (velocity=$\sqrt{(u^2+v^2)}$)

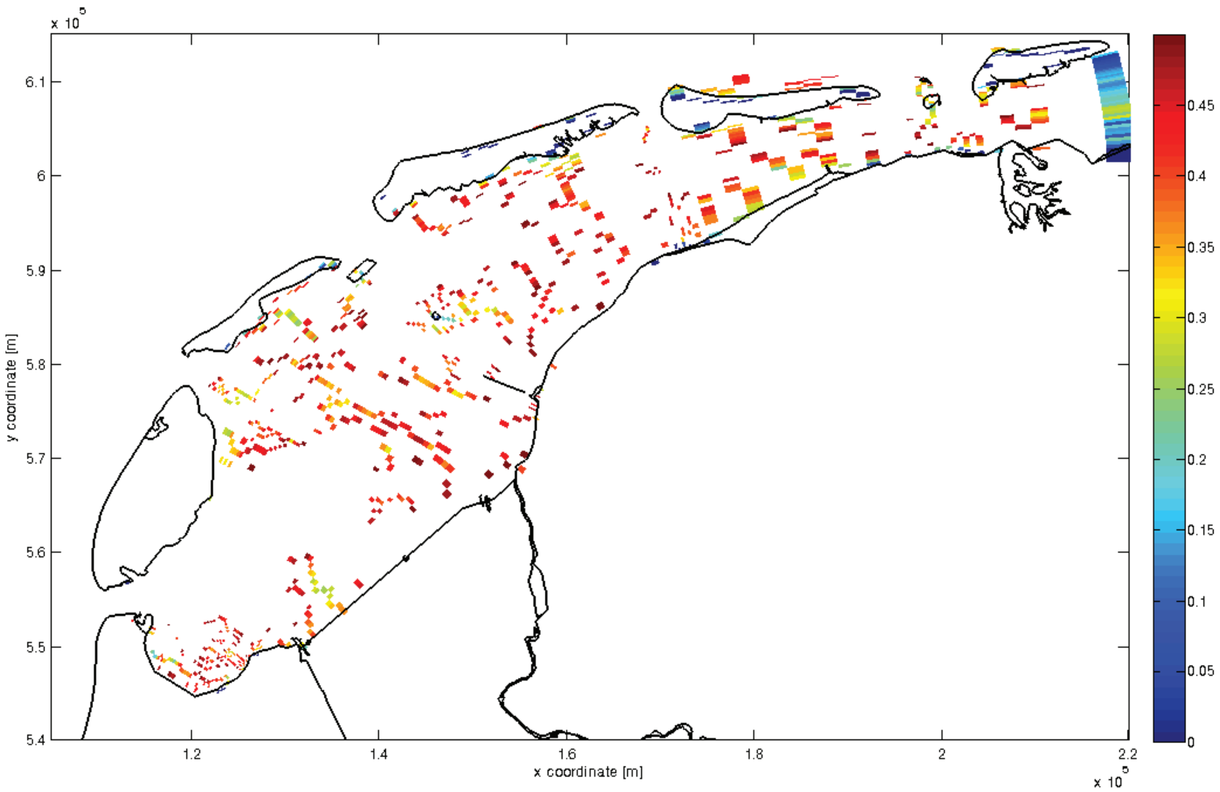


Figure 4.3 Minima (û<0.5 m/s) in the amplitude of the flow velocity in m-direction

Standard deviation

If the standard deviation of the flow velocity is considered, a similar problem occurs, see Figure 4.4. The standard deviation is a measure for the variation of the flow velocity[4]. The hydraulic tidal divide is located where the standard deviation is minimal and the tidal divide is then obtained visually: by drawing a line which matches the minimum standard deviation best. This line is more or less arbitrarily, because probably each person would draw a (slightly) different line. Nevertheless, this method is used in a couple of previous studies.

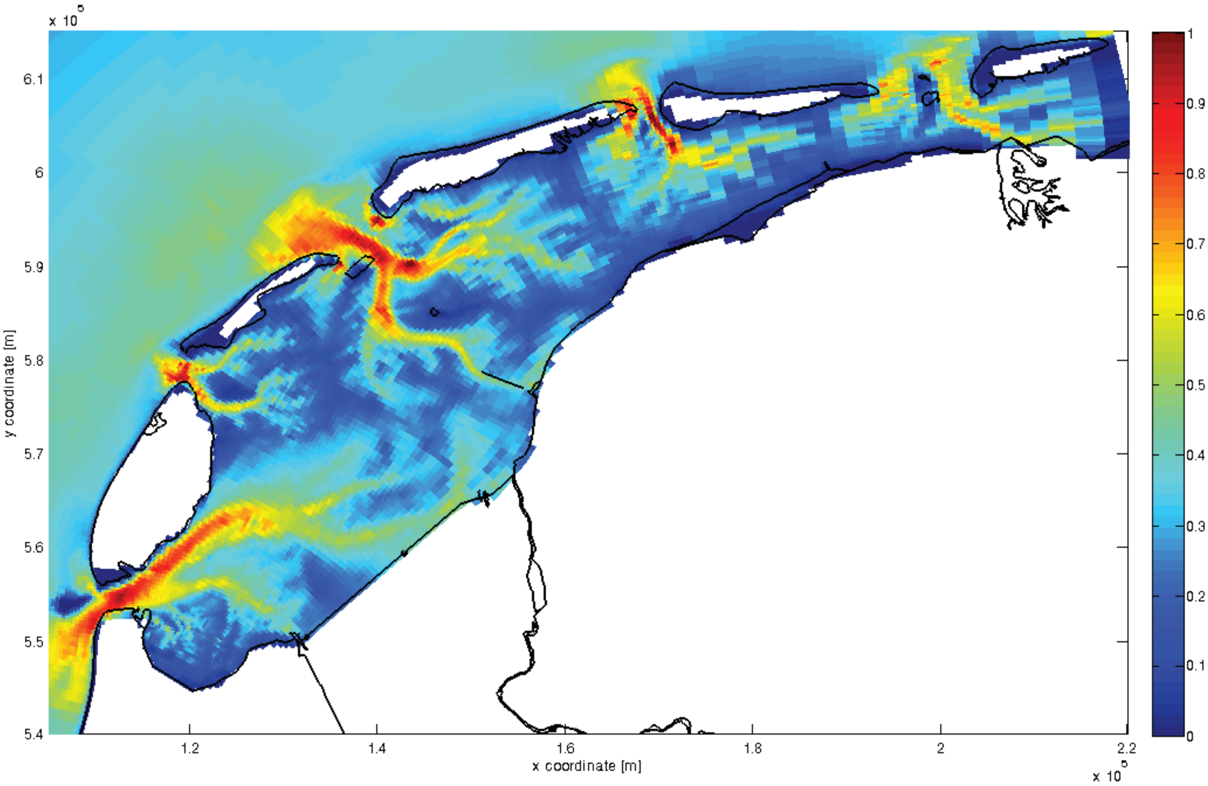


Figure 4.4 Standard deviation

Figure 4.5 shows the minima of the standard deviation determined in the m-direction. It gives the same view as for the maximum amplitude of the flow velocity, probably slightly better. The advantage of this method compared to the previous, is that it does not take the maximum value of the flow velocity which occurs in a certain period (in this case a month), but takes the measure for the spreading around the mean during the period considered. Thus, with this method all flow velocities occurring in this period are considered, instead of only the extremes. Especially when also wind (storms) is considered, this is a big advantage.

[4] The standard deviation is calculated for u- and v-direction, $\sigma = \sqrt{\frac{\sum_{i=1}^{N}(u_i - \overline{u})^2}{N}}$. Then, $\sigma=\sqrt{(\sigma_u^2+\sigma_v^2)}$.

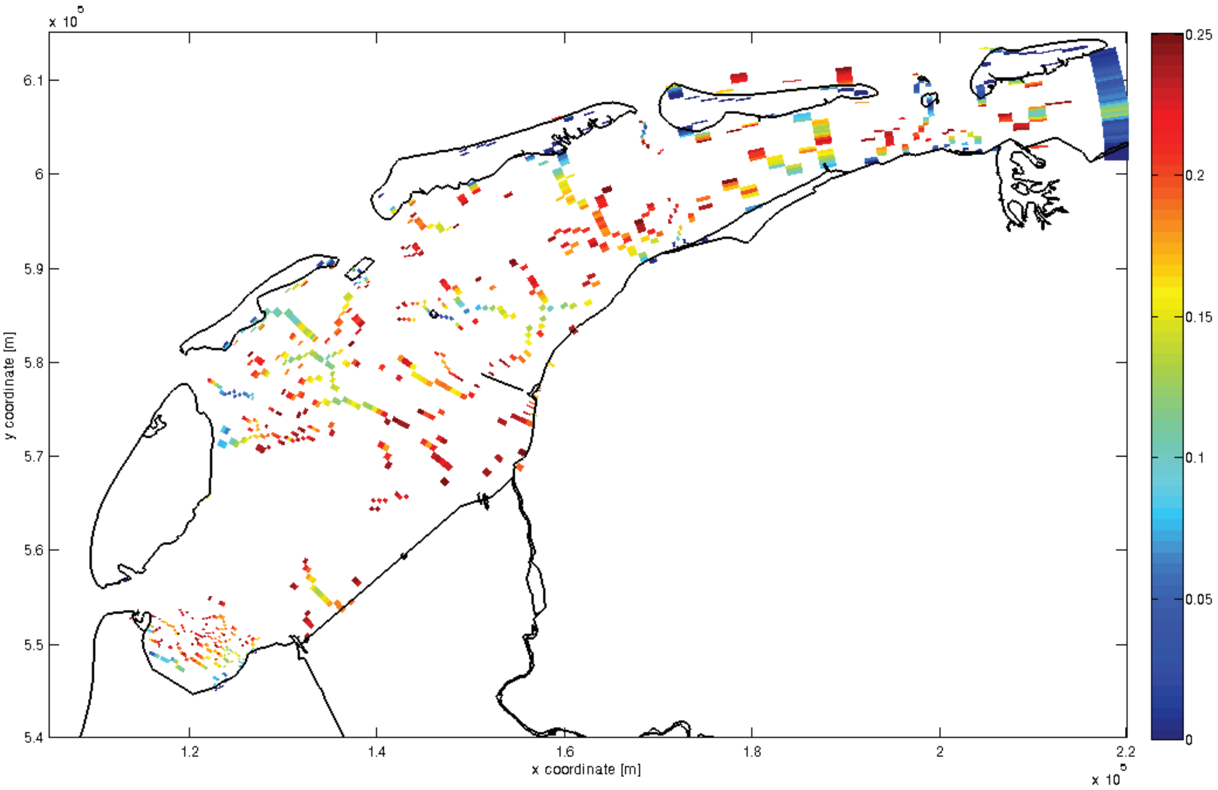


Figure 4.5 Minima (σ<0.25 m/s) in the standard deviation in m-direction

Maximum velocity in m-direction
The extreme values of the flow velocity are calculated in m- and n-direction (resp. u- and v-velocity). For tidal divides in the Wadden Sea (except for Eierlandse Gat), the m-direction is dominant (which is island-parallel). Therefore the extreme values of the u-velocity (two maxima in opposite direction) are calculated and the corresponding v-velocity is taken. Then a distinction is made between rising and falling tide. Due to the phase lag between flow velocity and surface elevation, the flow velocity for rising tide is directed towards instead of from the inlet and vice versa. The direction of these vectors indicates which cells 'belong' to which inlet.

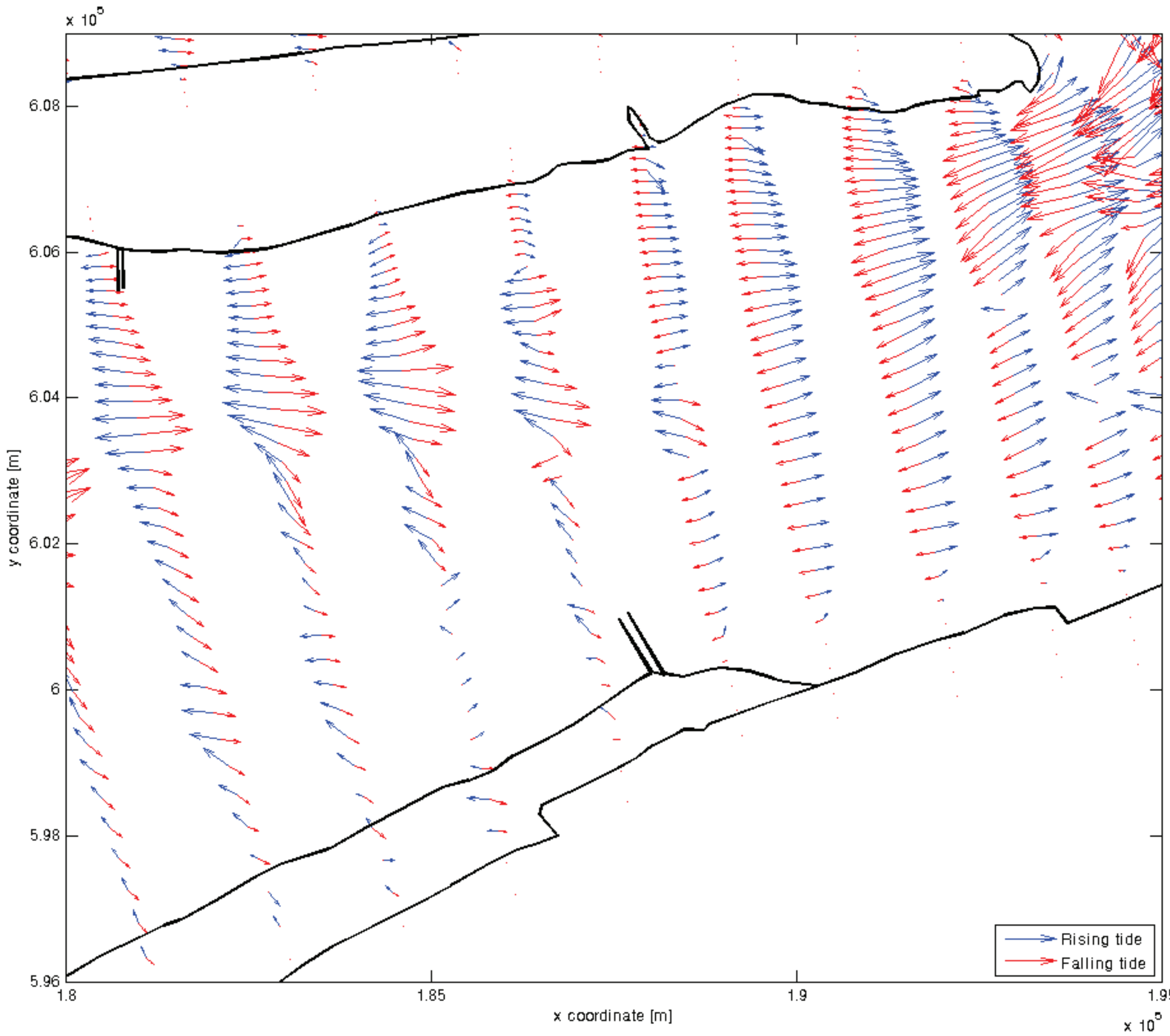


Figure 4.6 Largest u-velocity (and corresponding v-velocity) for the tidal divide behind Ameland

Figure 4.6 indicates the tidal divide behind the island of Ameland by the opposite velocity vectors. For the divides behind Terschelling and Ameland this method works reasonable. For the western Wadden Sea, this method is less clear. Figure 4.7 depicts the velocity vectors in the western Wadden Sea and these vectors are orientated more in circles instead of that they point at opposite direction. Probably this is due to the increased water exchange between the basins.

A disadvantage of this method is that it only considers maximum velocities which occur in the period considered.

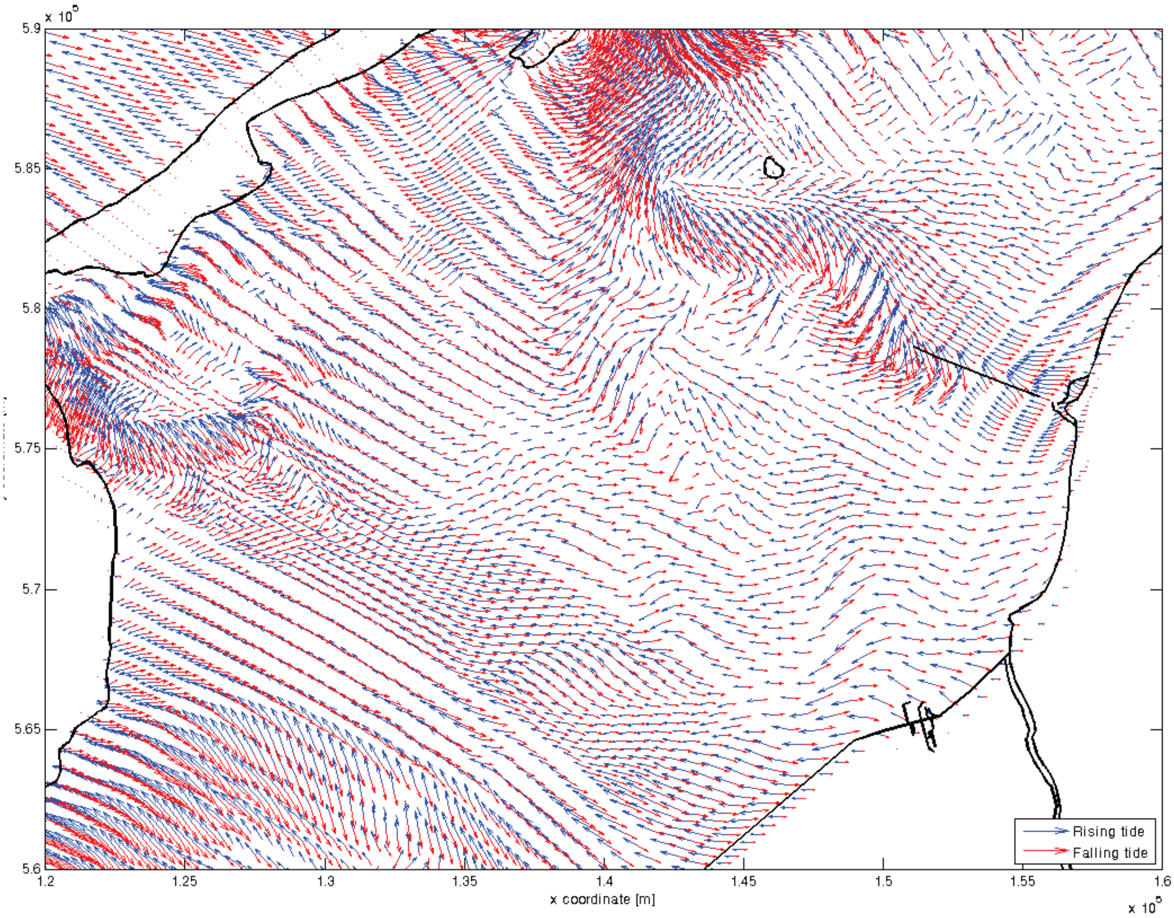


Figure 4.7 Largest u-velocity (and corresponding v-velocity) for the tidal divides in the western part of the Wadden Sea

Residual flow
Stanev et al. define the tidal divide by the location where the exchange of water is minimal. This can be calculated by residual flows. If the flow velocities over an exact number of waves are averaged, the residual flow is obtained. As can be seen from Figure 4.8 and Figure 4.9, it is not very clear where the tidal divide is located. Next to this, if the same amount of water is imported as exported, the residual flow is zero, but the flow velocities can still be very large.

A disadvantage of this method is that an exact (round) number of waves has to be taken, or a long period, otherwise the residual flow is 'polluted' by absolute values of the velocity. This practical aspect affects the accuracy of the method.

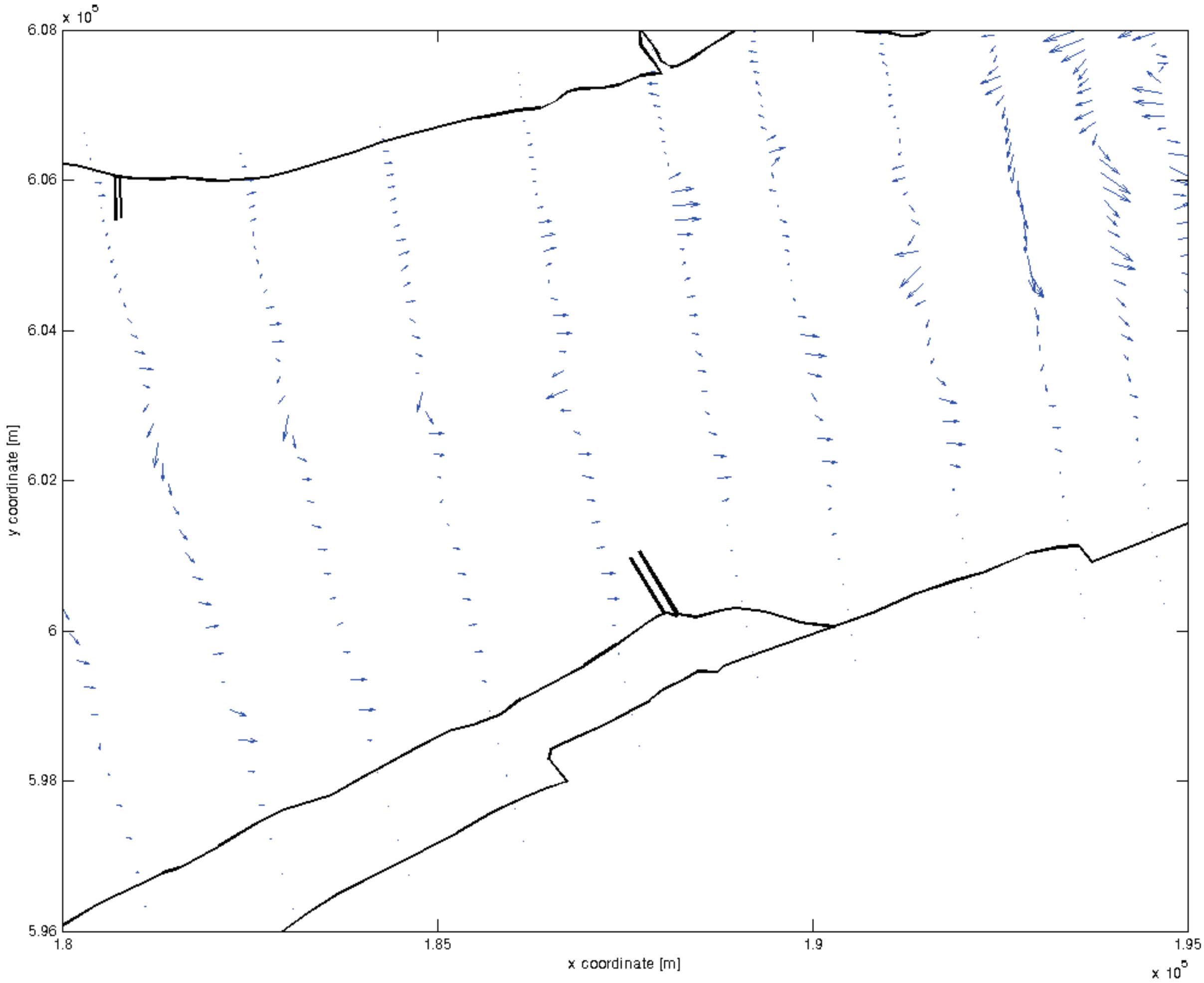


Figure 4.8 Residual flow pattern behind Ameland (summation of 30 min interval velocity)

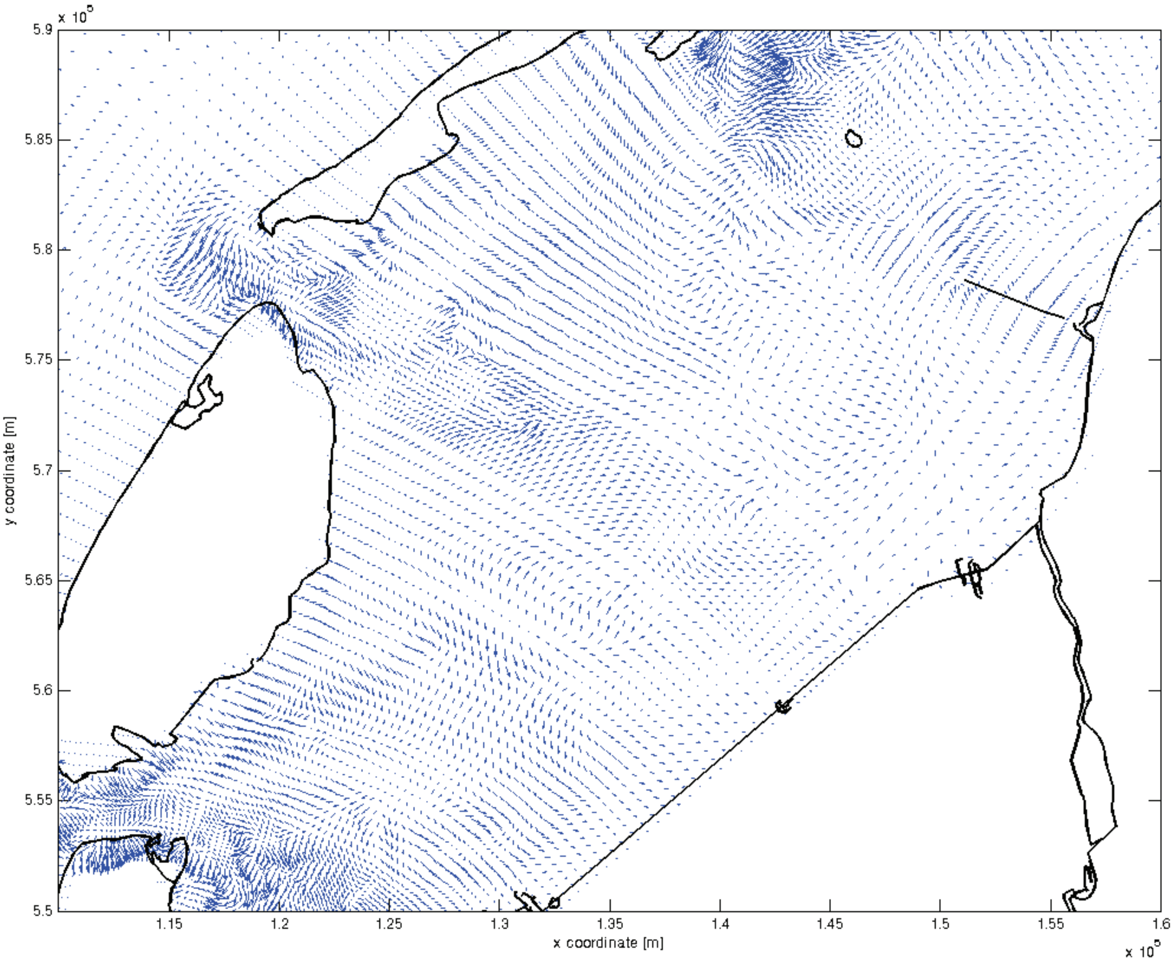


Figure 4.9 Residual flow pattern in the western part of the Wadden Sea (summation of 30 min interval velocity)

Tidal prism
With Delft3D the tidal prism is measured by taking the residual flow times the water depth. This parameter indicates the tidal divide by its smallest magnitude. This method also uses the residual flow and thus the same disadvantage turns up. Nevertheless, the method seems to give a good indication of the position of hydraulic tidal divide.

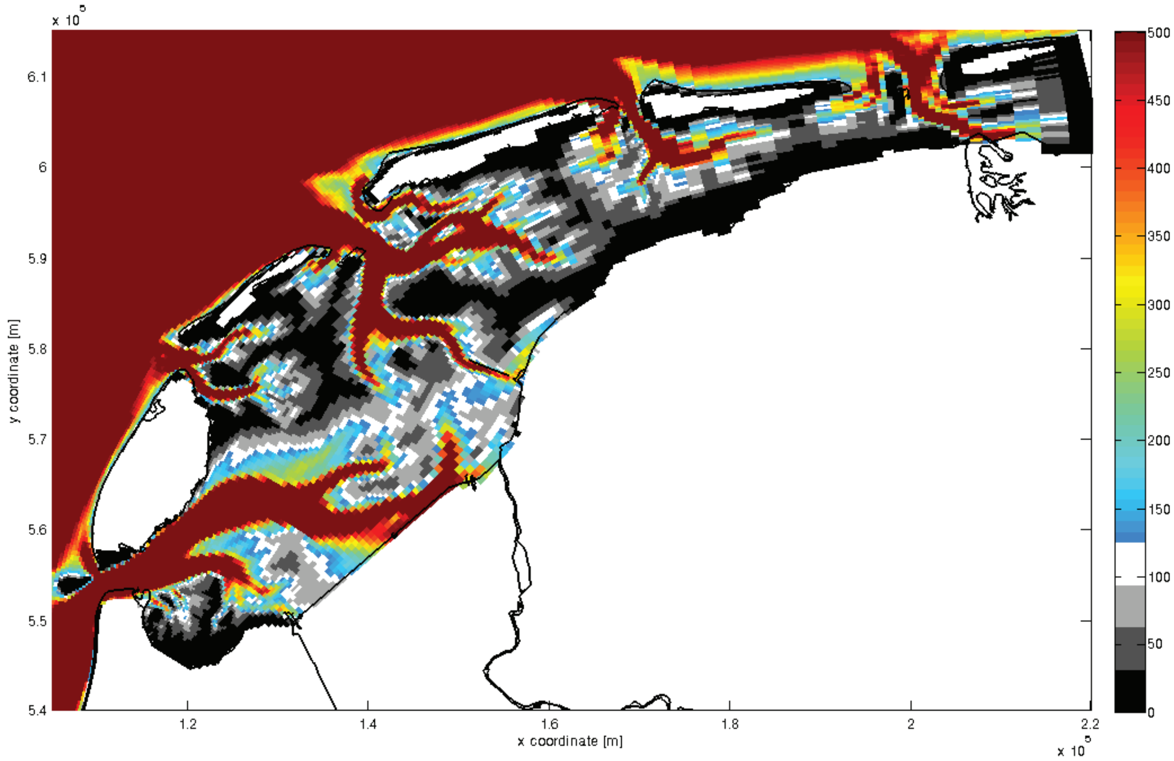


Figure 4.10 Location of hydraulic tidal divides defined by the tidal prism

The following considerations are taken into account when choosing the best definition for the hydraulic tidal divide:

- None of the methods gives a line for all the tidal divides in the Wadden Sea as outcome. In fact there is no line, but engineers desire a least arbitrary line.
- A method which uses all the flow velocities (or values of another parameter) in the period considered instead of only extreme values is preferable.
- Residual flow imposes a strict condition for the time steps considered: a round number of waves has to be considered, otherwise an error slips into the computation. Averaging over a long period reduces the error. But also a small time step should be used to accurate compute the residual flows. Therefore this method can better not be used for the determination of tidal divides.

Hence, the only option left is then the standard deviation of the flow velocity. Therefore this method will be used to determine the position of the hydraulic tidal divide.

To avoid lines representing the hydraulic tidal divide being too arbitrarily, one has to study the water movement and standard deviation plots in detail. For example, the location of all the branches of the apple-tree shaped channel system have to be noticed in order to make a distinction between local and basin-bordering tidal divides. By combining all this information, lines can be drawn which give the best representation.

In the following, the hydraulic tidal divides are drawn matching as much as possible the minima in the standard deviation as displayed in Figure 4.5. The line which is obtained is checked with all other information available, of which the whole standard deviation figure (like in Figure 4.4) is most important.

From this section the conclusion can be drawn when the hydraulic tidal divide is used as definition for a basin boundary, there should always be a location where this hydraulic tidal divide can best be defined in case a (partially) standing wave occurs in the basins. The fact that some hydraulic tidal divides are 'stronger' than others, can tell something about the exchange between the basins and the equilibrium of the basins. This strength can be indicated by the average value of the standard deviation over the tidal divide, which is another advantage of this definition.

4.2. Morphological tidal divide

Also for the morphological tidal divide a clear definition is searched. In this section different morphological tidal divides present in the bathymetry of 2006 are compared. The bathymetric data are subtracted from vaklodingen of Rijkswaterstaat, which are more accurate than the bed schematizations in Delft3D.

Until this section the morphological tidal divide was defined as the line with the highest bed level elevation. This definition has to be clarified somewhat. Sediment will settle at locations where the flow velocities are low, at any place in the basin. In principal, the flow velocities will decrease if the distance to the inlet increases. This implies that between two basins, a higher elevated area will be present. In the Wadden Sea the amount of flats is indeed largest in the back of the basins. In theory the highest point of this elevated area is the morphological tidal divide. In reality, the transition between basins is much more gradual, and it is hard to mark a line. Next to this, there can be spots with a higher bed level, which definitely are not located in between basins, but for example in between two branches belonging to the same channel system. So, not every high elevated point in a basin indicates the morphological tidal divide.

A morphological tidal divide is not a clear line, but consist of (interconnected) flats: spots where the bed level is elevated. Moving along a channel from inlet towards the tidal divide, the channel gets narrower and branches out into smaller channels, with even smaller branches connected to it. Van Veen (1950) described the channel-patterns in the Wadden Sea as apple-trees, see Figure 1.1.

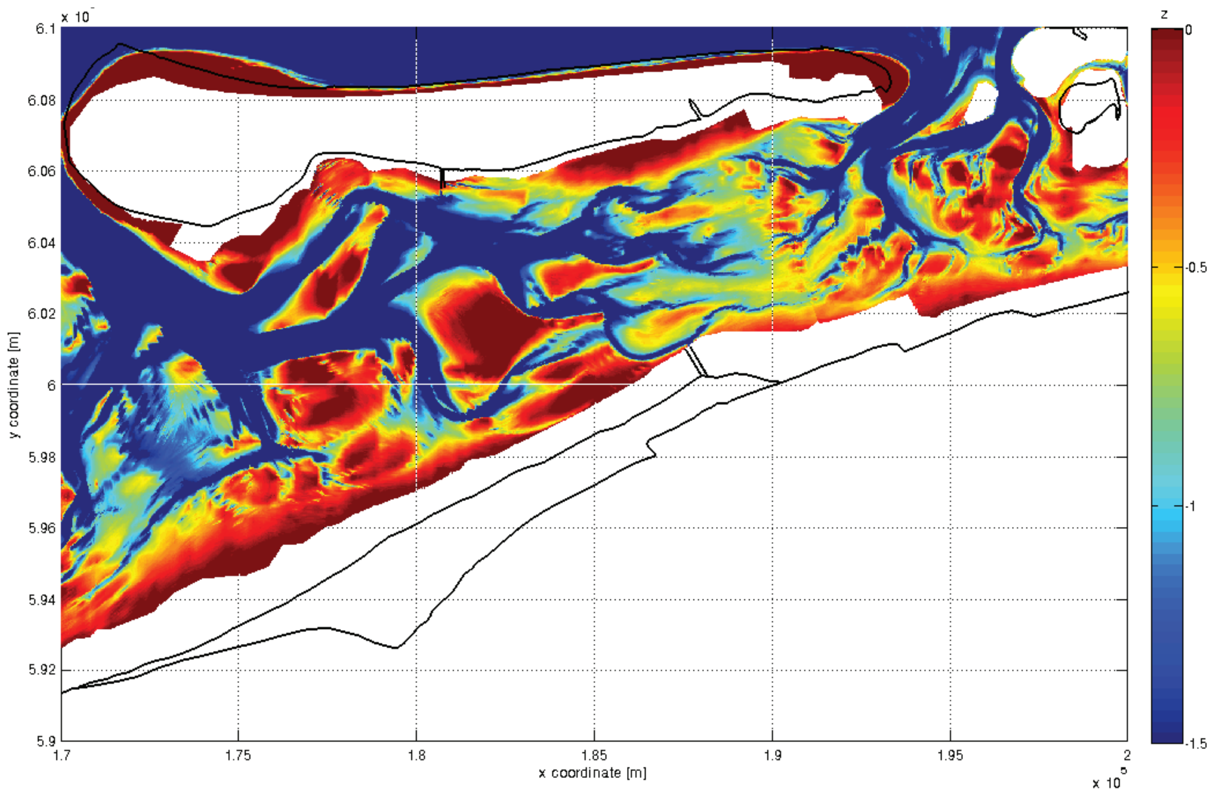


Figure 4.11 Bathymetry behind Ameland in 2005 illustrates the apple-trees of Van Veen and the spine-like shape of the morphological tidal divide

As long as the width of the Wadden Sea is small compared to the island length and the islands are relatively long, the channels approach the morphological tidal divide perpendicularly. Analogously to the apple-trees of Van Veen, the shape of a morphological tidal divide in this case looks like a spine or backbone; see Figure 4.11, Figure 4.12 and Figure 4.13.

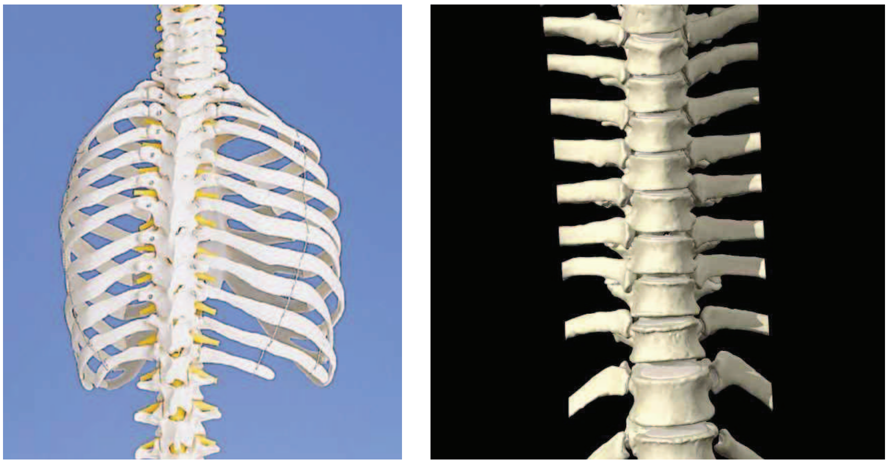


Figure 4.12 Two illustrations of a spine or backbone with adjacent ribs

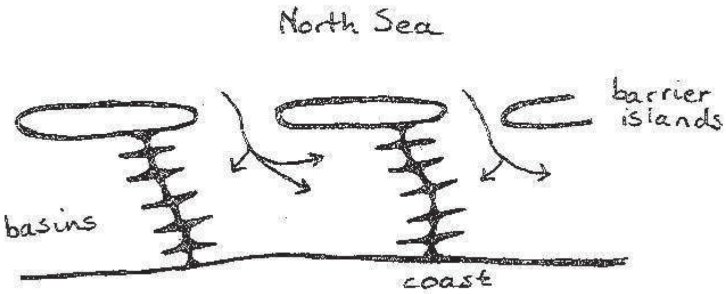


Figure 4.13 Drawing of spine-shape in Wadden Sea

Instinctively, one can define a line representing the morphological tidal divide in Figure 4.11 on the previous page. Probably, one would subconscious look for the centre line of the spine and correct for the height of the flats. From this figure one might also expect that the morphological tidal divide is just the highest point in the bed level in between the apple-trees. Figure 4.14 shows this is not necessarily the case, because here the centre line of the spine does not coincide with the highest bed level. This illustrates why it is so hard to find a generic method for defining the position of the morphological tidal divide.

Studying Figure 4.11 in more detail, the morphological tidal divide looks like to be higher on the eastern side of the centre line. The morphological tidal divide behind Terschelling on the other hand has a centre of gravity which is more in line with the centre line of the spine. This might also be an indication for the equilibrium or the transition of the morphological tidal divide. This is not verified in this thesis, but it is an observation from the shape of the morphological tidal divide.

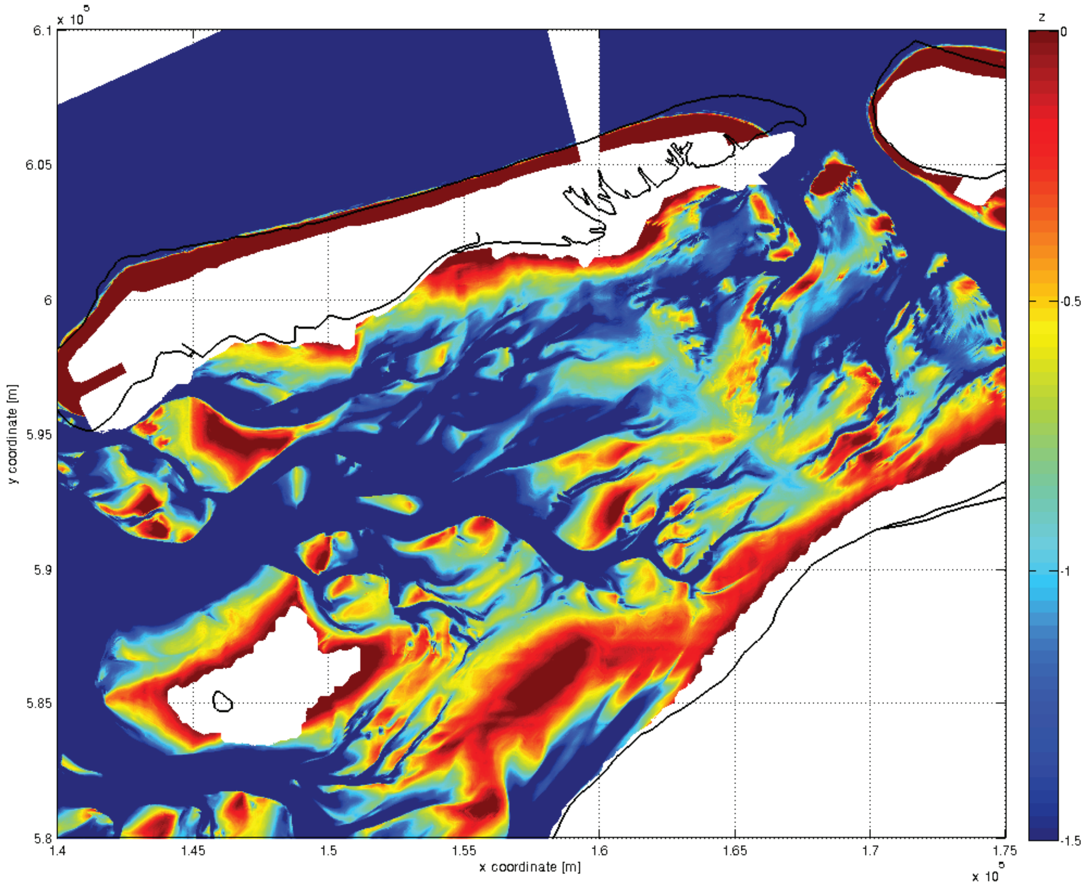


Figure 4.14 Bathymetry behind Terschelling in 2004

In the eastern Wadden Sea, the spine-shape shows good resemblance with the morphological tidal divides. In the western Wadden Sea, see Figure 4.15, this shape is harder to find. The morphological tidal divide between Eierlandse Gat and Vlie basin is surrounded by channels which approach the tidal divide perpendicular and the spine-shape is present. The morphological tidal divide between Marsdiep and Eierlandse Gat is not perpendicularly approached by channels and therefore the spine-shape is harder to find. Between Marsdiep and Vlie, the morphological tidal divide is less pronounced (less high) and the branches are more intertwined. The determination of the morphological tidal divide by the spine-shape is harder, but is not impossible. Below two images of the tidal divides in the western Wadden Sea are shown, with different colour bar limits.

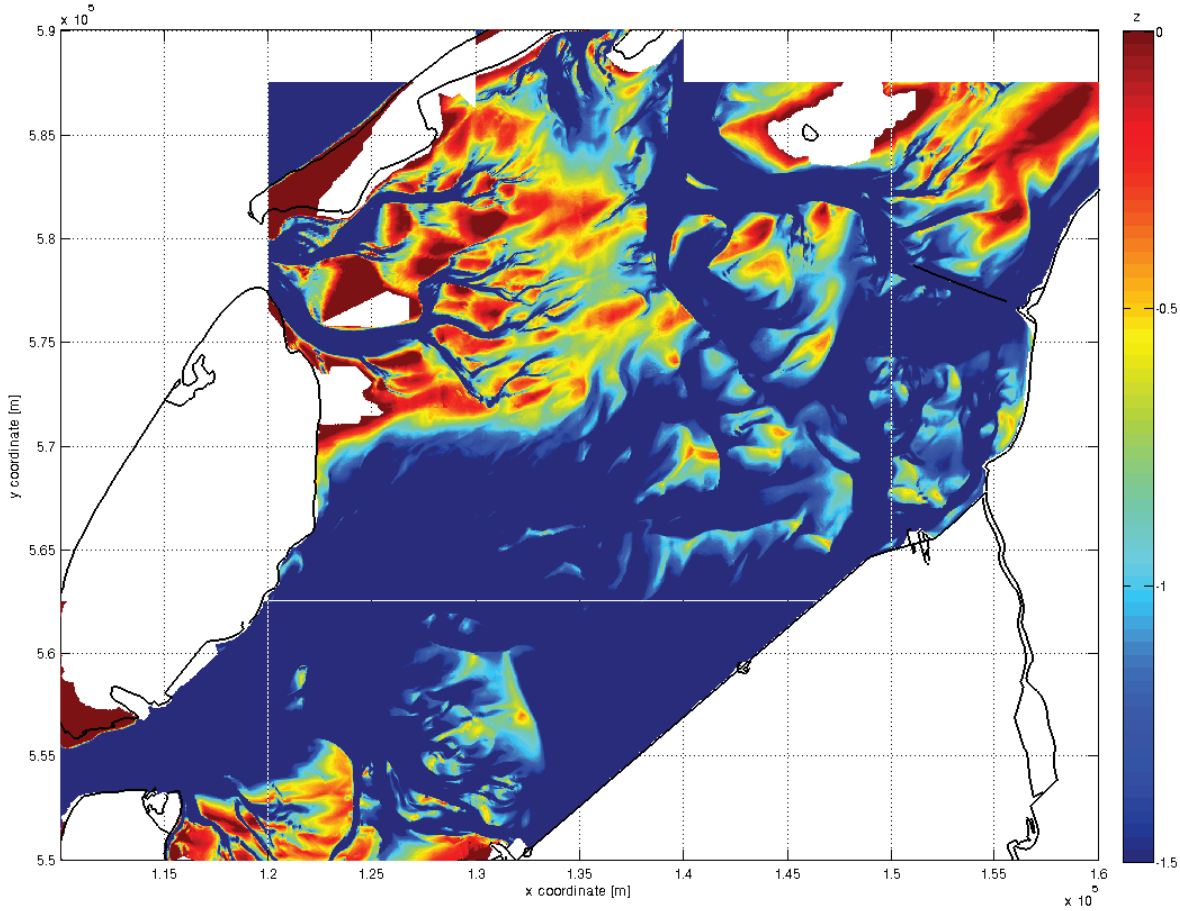


Figure 4.15 Bathymetry of 2003 in the western Wadden Sea

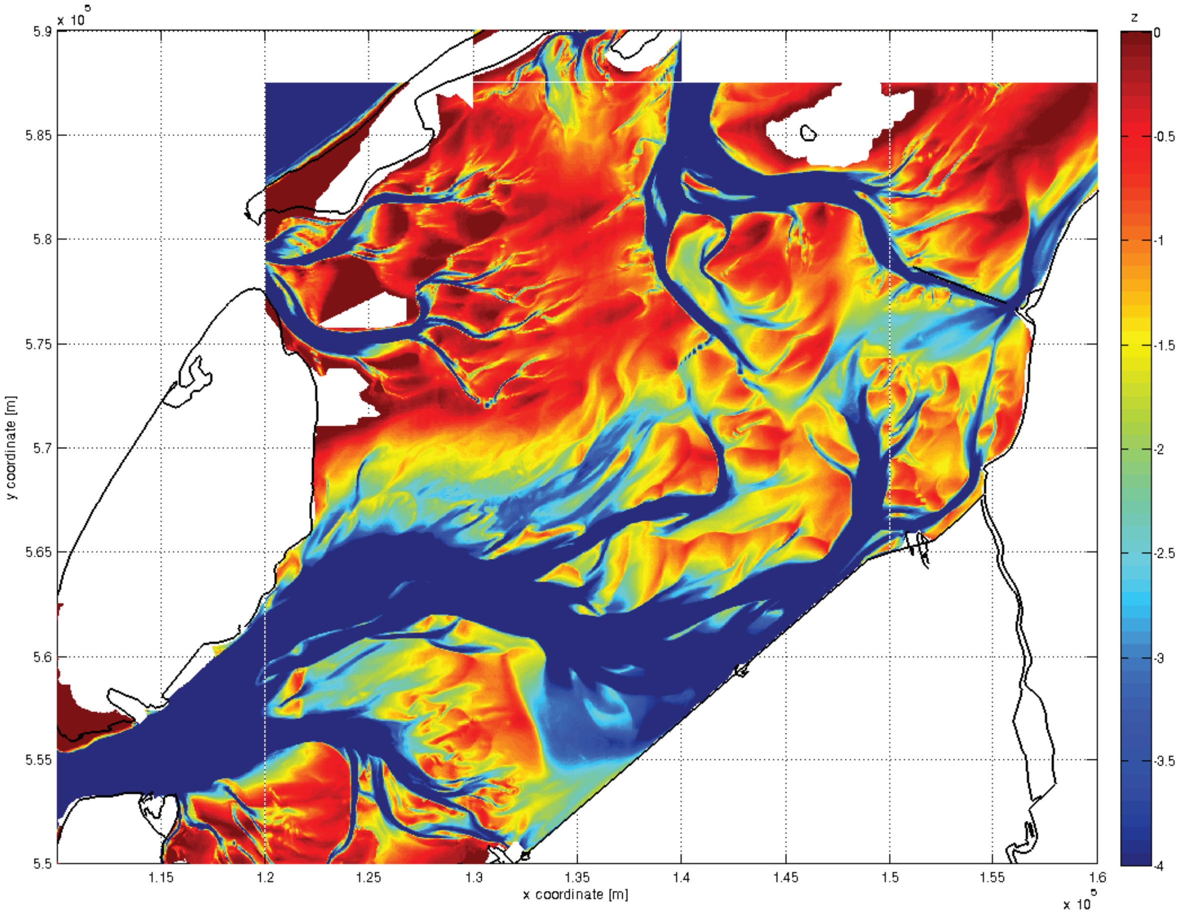


Figure 4.16 Bathymetry of 2003 with different colour bar

From this section the conclusion can be drawn that the bed level in between the basins in the Dutch Wadden Sea has a spine-like shape. The morphological tidal divide is defined as the centre line of this spine, which is not necessarily the highest point in the bed level. This line is not a basin boundary, because the basin boundary is already defined by the hydraulic tidal divide. However, it does give information about the movement of the hydraulic tidal divide. In fact, in this thesis the morphological tidal divide is defined as the footprint of the hydraulic tidal divide. Hydrodynamic changes are a lot quicker than morphological changes, hence the morphological tidal divide in fact shows where the hydraulic tidal divide is or *has been*. If the hydraulic and morphological tidal divide do not overlap, this is an indication that the divides are moving. Van de Kreeke (1990) and Van de Kreeke et al (2008) showed the importance of the existence of a morphological tidal divide on the stability of the system. Hence, the height of the morphological tidal divides is relevant in relation to the equilibrium of the basins. This means that both the position and the height of the morphological tidal divide are important indicators of the equilibrium of the basins.

Maybe the reader is wondering whether the spine-shape is also applicable to the hydraulic tidal divide. This might be possible, but a practical limitation is the grid size. The grid is too coarse to define the hydraulic tidal divide with the spine-shape. If the grid is refined, one has to cope with increased computational time. Therefore in this thesis, the hydraulic tidal divide is defined by the minima in the standard deviation.

5. Movement of tidal divides in the Dutch Wadden Sea

In this chapter the evolution of the hydraulic and morphological tidal divides are studied in the period directly after the closure of the Zuider Sea until present. It will give more insight in the movement of hydraulic and morphological tidal divides with respect to each other. In the Delft3D model, which is used to study the hydrodynamics, the Afsluitdijk is present in all computations. This means that the 1926 model runs, which are expected to represent the situation before closure, have to be interpreted as the 1932 situation.

5.1. Hydraulic tidal divides

Figure 5.1 shows the line representation of the hydraulic tidal divides for each year. The behaviour and movement of the hydraulic tidal divides are illustrated by the position of these lines. Observations described in this section are always coupled to the whole picture of the standard deviation, see Appendix C, and not only to the lines as displayed below. Next to this, it has to be said that the lines representing the hydraulic tidal divide can be located at either side of the grid cell with the smallest standard deviation.

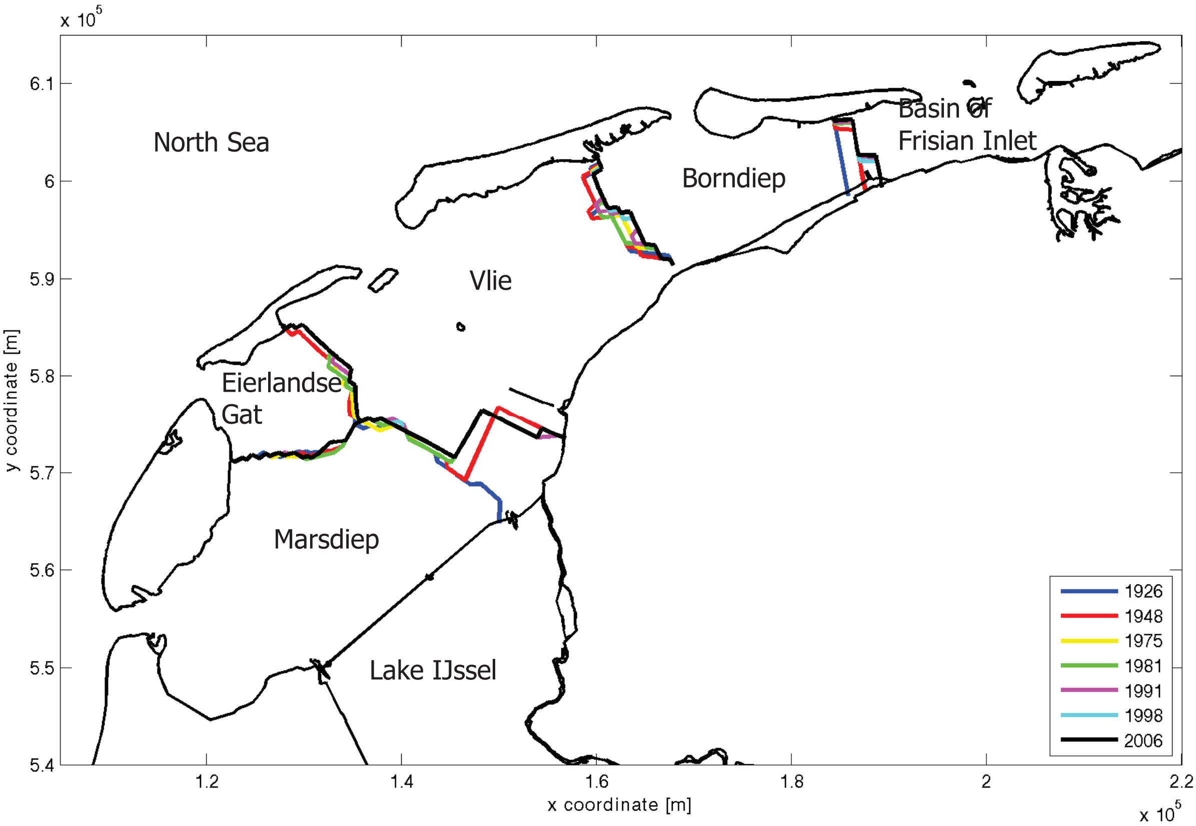


Figure 5.1 Hydraulic tidal divides in the period 1926-2006 represented by a line

Of course, the largest changes are observed at the tidal divide between Marsdiep and Vlie. The hydraulic tidal divide of '1926' (which is simulated with the Afsluitdijk and in fact resembles the situation of 1932) is located at the position where it is believed to be located prior to closure. Apparently, the hydrodynamics are governed by the bathymetry to a large extend. But, looking at the figure of the standard deviation, see Figure 5.2, one can see that also at the later location of the hydraulic tidal divide (close to the Pollendam), the standard deviation is already very low. Probably, both these locations were a *local* hydraulic tidal divide prior to closure, located at either side of the channel flowing from Vlie inlet into the Zuider Sea. Directly after the closure, an eastward expansion of the channels near Kornwerderzand is observed. This is the cause that only the part of the hydraulic tidal divide close to the Frisian coast has moved and the part next to the Eierlandse Gat has kept the same position. The branch of the Vlie channel system has enough strength here to withstand the push from Marsdiep, at least until present. Further expansion of the Marsdiep in this direction is influenced by the Pollendam and the dredging along the Pollendam, which artificially elongates the Vlie branch. The adaptation of the hydrodynamics at this location is mainly already accomplished in 1948, afterwards the hydraulic tidal divide did not shift a lot.

In the Marsdiep basin other large changes are that the flow velocities have become lower in the Doove Balg (channel) and higher near Lutjeswaard (flats). To speak in Van Veen's language, the branches of the apple-tree of Marsdiep (which seems to be more like a poplar as observed in the estuaries in the south of the Netherlands) are blown more to the northeast.

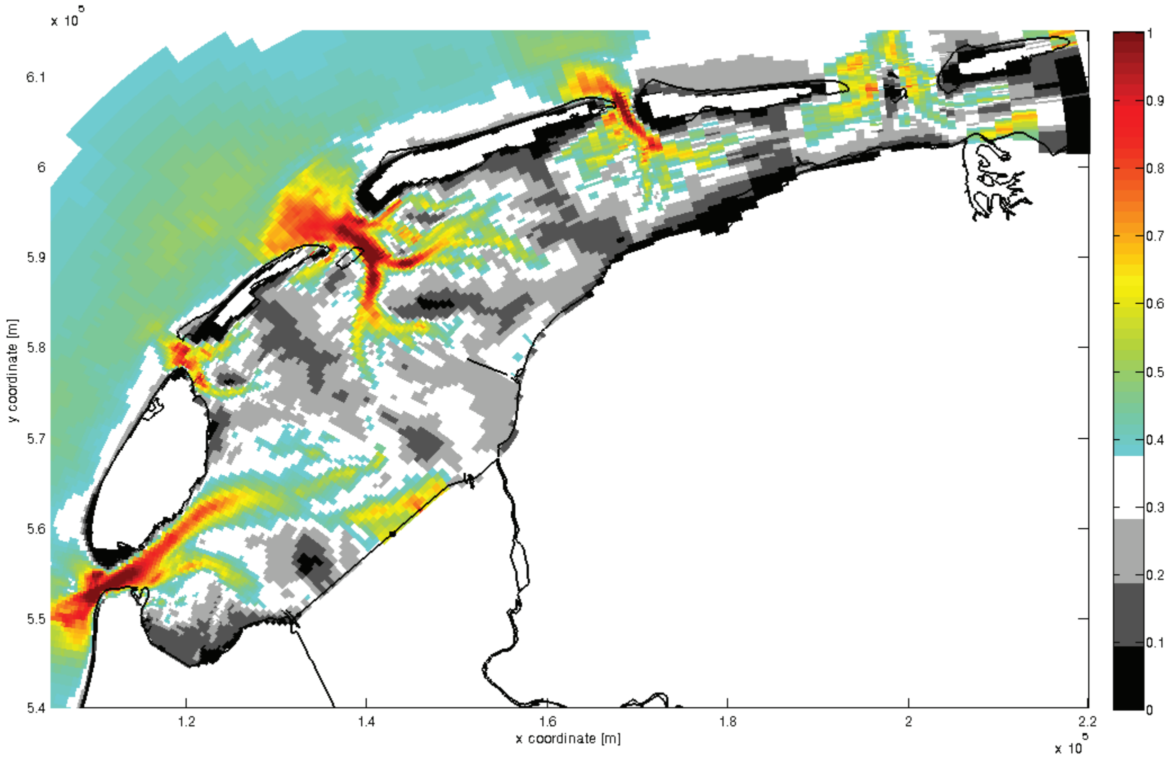


Figure 5.2 Standard deviation for 1926

Remarkable are the small changes near Eierlandse Gat. This basin, which is located relatively close to the Afsluitdijk, has not largely been influenced by the basin size reduction of Marsdiep and Vlie. From literature it is known that this basin always has been relatively autonomously, whereas the Marsdiep and Vlie basin were interacting to a large extend. In the last 80 years the hydraulic tidal divides point at an increasing basin size of Eierlandse Gat, to which the eastward movement of the tidal divide between Eierlandse Gat and Vlie mainly contributed. The 'width' of this hydraulic tidal divide seems to decrease after 1926 and increases later on. This means that on average the flow velocities first have increased in this area and decreased again later on. The tidal divide between Eierlandse Gat and Marsdiep has not changed a lot, especially the location directly behind Texel island looks stable. Probably the hydraulic and morphological tidal divide are located at the same position here. Although the line does not show a large shift, the plots of the standard deviation show that inside the basin, the branches have expanded. However, this did not have an effect on the lines representing the boundaries between the basins.

In the eastern Wadden Sea, an eastward movement of the hydraulic tidal divide between Borndiep and Frisian Inlet can be observed. This shift has mainly occurred in the years 1926-1975, after this period the position of the hydraulic tidal divide is more or less stable. Note that the grid is coarse there, due to this the shift of this divide can be overestimated. The eastwards shift of the divide is caused by the closure of the Zuider Sea, which more or less pushed all basins eastward. The tidal divide behind Terschelling does not show a chronological eastward shift, but overall the divide moved eastward. The jumping of the hydraulic tidal divide in time from east to west and vice versa might be due to the fact that the differences in standard deviation are very small and the minimum can jump easily in subsequent years. Between 1926 and 2006 the hydraulic tidal divide behind Terschelling has become narrower, which implies that the area with very low flow velocities has become smaller. This is due to the eastward expansion of the Vlie channel system, which more or less squeezes the hydraulic tidal divide and also pushed the westerly channels of Borndiep in eastward direction.

Another trend in the eastern Wadden Sea is that along the Frisian coast, from Harlingen in eastward direction, the flow velocities are reducing. This facilitates the growth of marshes on this coastal strip. Analysis of the morphological changes can confirm these observations later on. In fact the channel systems are pushed more against the barrier islands here. This might be a reaction to the hindered movement of islands towards the coast, which is the natural response to sea level rise. This is hindered by human intervention, which is aimed to keep the islands at place.

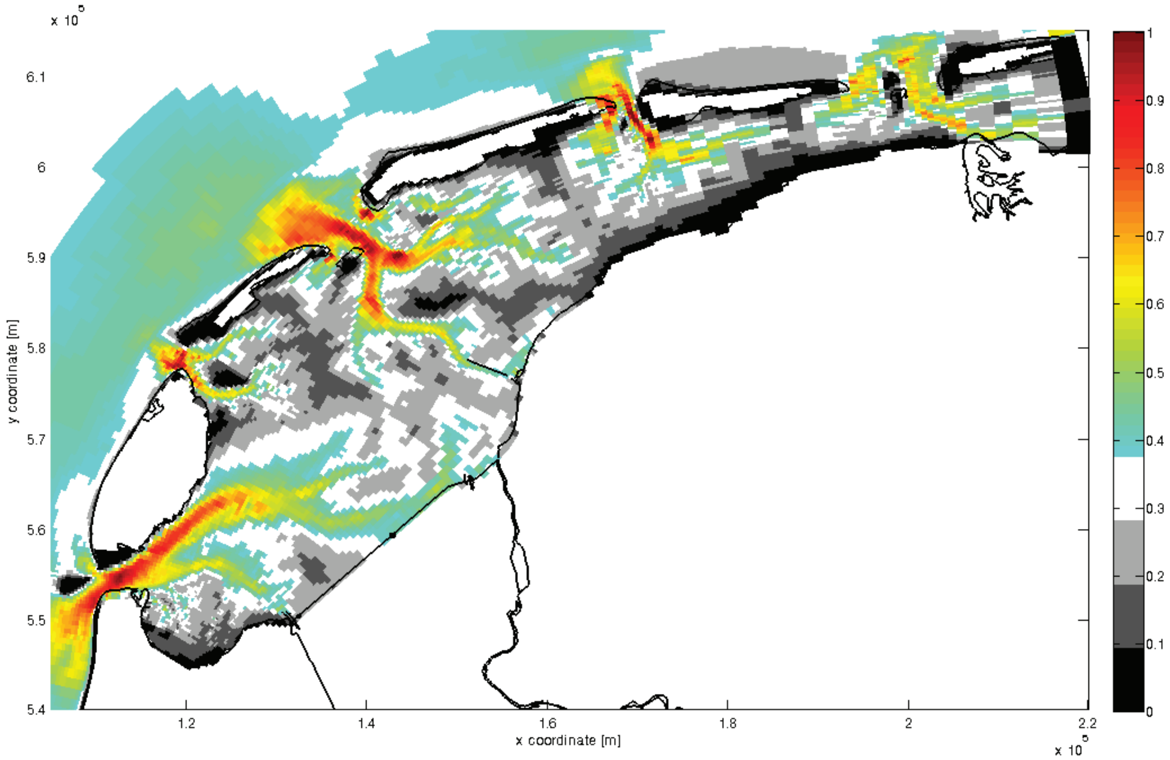


Figure 5.3 Standard deviation plot for 2006

Conclusions from this analysis, is that almost all hydraulic tidal divides moved in eastern direction. This behaviour is triggered by the cyclic movement of the islands in the Wadden Sea, which used to move eastwards as well, but are now more or less kept at position by human interference. In addition, the closure of the Zuider Sea removed the 'anchors' which kept the Vlie and Marsdiep channel systems at place and gave them the opportunity to move in eastward direction. Comparison of all hydraulic tidal divides shows that the hydraulic tidal divide between Marsdiep and Vlie has the largest standard deviation, i.e. the highest flow velocities. This is due to the large amount of water exchange between the basins, which is confirmed by results of previous studies.

The Marsdiep and Eierlandse Gat show an increase in basin size (in the period '1932'-2006). The Vlie basin reduced in size and the Borndiep is more or less equal in size. The expansion of the Marsdiep in the direction of the Vlie basin seems to be facilitated by the position of a former local hydraulic tidal divide near the Pollendam. The 1926 simulation shows the position of the hydraulic tidal divide before closure, although this simulation is made with presence of the Afsluitdijk. This indicates the relatively large influence of the bathymetry on the position of the hydraulic tidal divide.

Observations from these sections have to be coupled to the movement of morphological tidal divide, to see whether they show a consistent behaviour.

5.2. Morphological tidal divides

The 'vaklodingen' of Rijkswaterstaat contain bathymetric data of the Wadden Sea for the period 1926-2006. The Wadden Sea is divided in different boxes, which contain bathymetric data of measurements taken at different moments. For each tidal divide, a collage of the boxes with different measuring days is made to achieve the most optimal representation of the bathymetry of a certain year. The combinations are listed in appendix B. The bathymetry figures are displayed in Appendix D.

It is good to realize that going back in time, the measuring techniques were less accurate and therefore older data are less reliable. The data available are collected on different days and in different seasons. It can make a difference if the data are collected directly after a big storm or a storm season, or after a quiet period. Nevertheless, the changes in bathymetry are large enough compared to the measuring errors to recognize trends in the morphological evolution.

The tidal divides will be described by the changes which can be observed in time. The focus here lies on the trends which can be observed regarding the movement of the whole spine-shape structure being the morphological tidal divide. These qualitative changes will be checked with the movement of the lines which represent the morphological tidal divide.

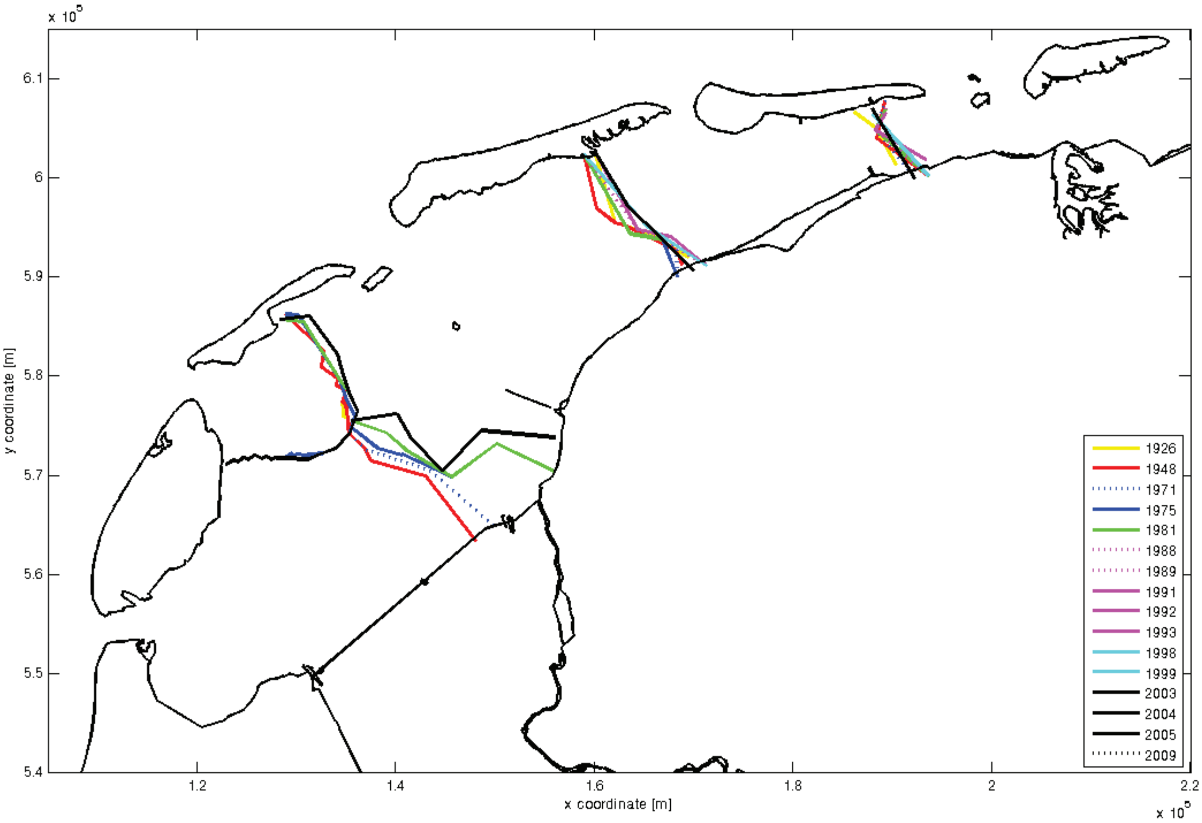


Figure 5.4 Morphological tidal divides in time represented by lines

The morphological tidal divide between Marsdiep and Vlie has been affected the most by the closure of the Zuider Sea. As mentioned before, the wave propagation has changed drastically and this has its impact on the position of the hydraulic and morphological tidal divide. Where prior to the closure the two waves shared the same basin, now they are both competitors trying to gain basin area. This resulted in an adaptation of the hydrodynamics which was relatively quick, as was described before. The morphological changes follow the path of the hydraulic tidal divide, but adaption is slower, as is shown in Figure 5.4. The hydraulic tidal divide of 1932 was located at the position of the morphological tidal divide, which indicates the large constraint the morphology lies on the movement of the hydraulic tidal divides. Apparently the flow velocities on the morphological tidal divide increased, but were still not high enough to shift the hydraulic tidal divide. It took some time to erode the morphological tidal divide, after which the hydraulic tidal divide could move. This is also observed in the bathymetric changes. From 1926 (prior to closure) to present, first it looks like the morphological tidal divide flattened at its former location, then it heightens again at its location as where it is today. This might be an indication that the morphological tidal divide has arrived at its new location, i.e. its equilibrium position after the closure of the Zuider Sea. The fact that the hydraulic tidal divide is almost at the same position as the morphological tidal divide strengthens the believe that the position of this tidal divide is close to equilibrium. Heightening of the morphological tidal divide will probably continue. This might have an influence on the position of the hydraulic tidal divide, because it is already mentioned that the bathymetry has a large influence on the position of the hydraulic tidal divide.

In fact, the morphological tidal divide here made a counter clockwise rotation, because its most seaward end is hold more or less in position by the tidal divides surrounding the Eierlandse Gat.

Further studying the morphological changes in the Marsdiep basin makes it clear that the channels which were crossed by the construction of the Afsluitdijk have been filled in. Also the flats north of the channel Texelstroom have become higher. The channel connecting Marsdiep to Vlie basin (Scheurrak) has becomes shallower and narrower, probably due to increased importance of the Texelschaar. These observations are in accordance with Oost and Kleine Punte (2004), as described in chapter 2.2.

When the figures of the bathymetry and not only the lines are studied, it can be observed that the morphological tidal divide between Marsdiep and Eierlandse Gat has become orientated more in island-parallel direction in the last 80 years. Adjacent to the island of Texel has always been a high morphological tidal divide. This high part has been elongated, which means an average heightening of the tidal divide. The morphological tidal divide between the Eierlandse Gat and Vlie inlet seems to have decreased in height directly after the closure of the Zuider Sea. After 1948, the morphological tidal divide has heightened again. Looking at the lines representing the centre line of the morphological tidal divide, a small eastwards shift can be noticed. This is due to the eastward expansion of the Eierlandse Gat channel system.

Inside the borders of Eierlandse Gat the channel system seems to have expanded. This can be explained by the equilibrium relations. From other studies (Van Geer, 2007) it is known that the Eierlandse Gat is subject to an increase of the tidal range. The movements of the basin boundary mainly results in an increase of flat area. The growth of basin area and the increased tidal range result in an increased tidal prism. Due to this the channel volume has to increase. This is also observed in the vaklodingen data, which shows an increase of channel area inside the basin. Hence, the observations of the vaklodingen data are consistent with theory and results found in previous studies.

In the eastern Wadden Sea, the morphological tidal divide behind Terschelling the tidal divide has also shifted eastward and the spine-shape has become wider. Probably the basin is reacting to the loss of basin area at the western side by moving eastward. The fact that the morphological tidal divide is becoming wider (which means that a larger part is getting higher), might indicate that the morphological tidal divide stays behind with the hydraulic tidal divide, which moved eastward.

The tidal divide behind Ameland shows a shift to the eastside in the last twenty years. Before this 20-year period it is hard to see any shift, only the height of the morphological tidal divide has changed. The morphological divide has become higher. The lines representing the morphological tidal divide are less accurate here due to large grid sizes.
In the period 1927-2006 the morphological tidal divide behind Schiermonnikoog seems to have heightened and in this way has also become broader. The location of the tidal divide did not change a lot. This morphological tidal divide is not studied in much detail, because the hydraulic tidal divide behind this island is not studied. For more information the reader is referred to Oost (1995).

The changes in the hydraulic tidal divides showed a decrease in flow velocities along the Frisian coast north of Harlingen. In the same period, a bed level heightening at the same location can be observed from the vaklodingen data. This confirms the observations from chapter 5.1.

Overall it can be concluded that the morphological tidal divides in the Dutch Wadden Sea are relatively high, except the morphological tidal divide between Marsdiep and Vlie. Most morphological tidal divides recently have the tendency to become higher, which is an indication that they grow towards an equilibrium. The heightening of the morphological tidal divides can also be a response to sea level rise. Whether the morphological tidal divides are also getting higher relative to the actual water levels, which also have the tendency to increase, see Van Geer (2007), is not considered in this thesis.

The interpretations from the bathymetric data have to be taken with care, because the dataset is relatively small (6-10 years) and measurements are taken with different measuring techniques and accuracy.

5.3. Position hydraulic vs. morphological tidal divide

Because the position of the hydraulic tidal divide with respect to the morphological tidal divide is an indicator for the equilibrium state of the basins, they are studied for the bathymetry of 2006. In the previous pages, the changes in hydrodynamics and morphology where described separately. When combining both observations, one has to keep in mind that the water levels (HW and LW) are not fixed, but do also change in time (see Van Geer, 2007). In general, basins try to keep up with sea level rise and thus with increasing HW and LW levels.

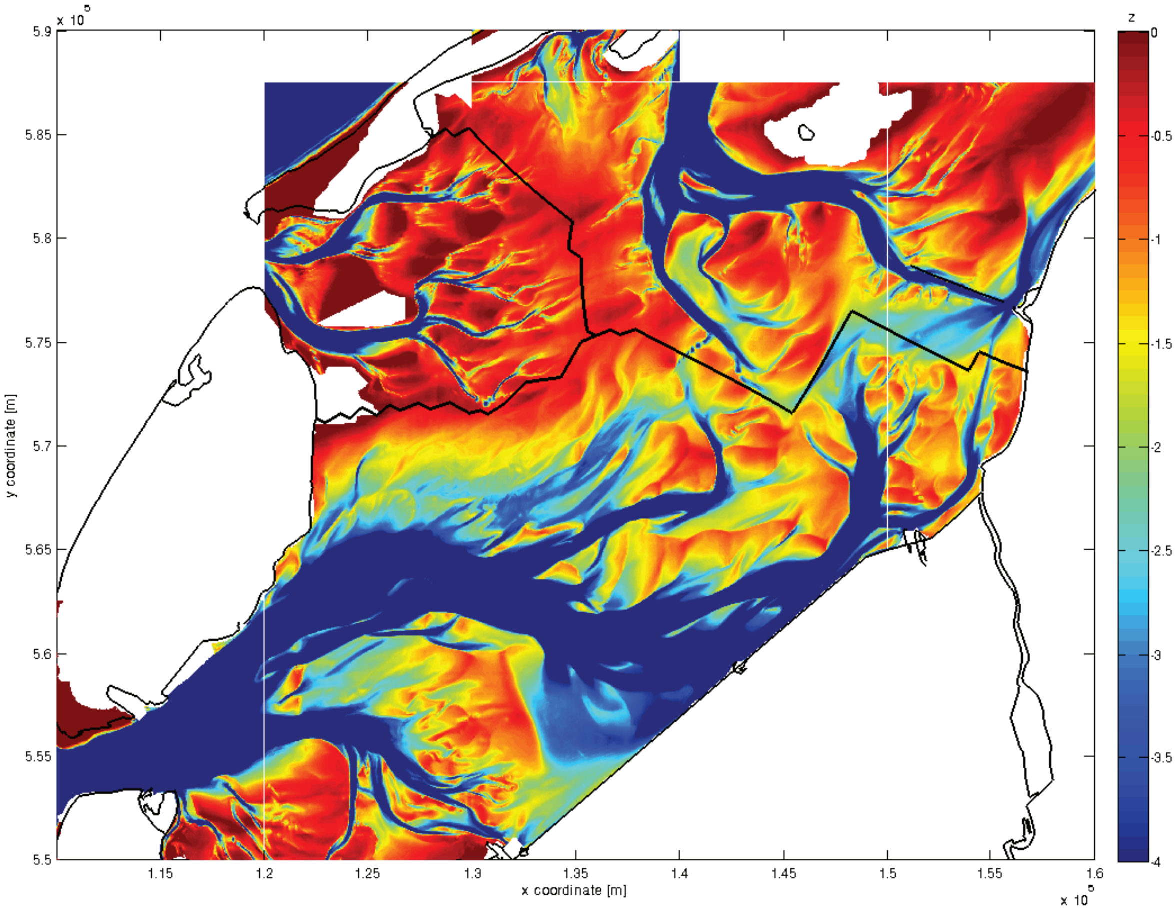


Figure 5.5 Bathymetry of 2003 obtained from vaklodingen data and position of hydraulic tidal divide 2006

In Figure 5.5 the three tidal divides in the western Wadden Sea are shown. The hydraulic and morphological tidal divides bordering the Eierlandse Gat basin have more or less the same position, indicating that this basin is not changing quickly or maybe is more or less in equilibrium. The tidal divide are also relatively high, which strengthens the believe that this basin is not far from equilibrium. The morphological tidal divide between Eierlandse gat and Vlie inlet seems to be located even further eastward than the hydraulic tidal divide. This can be explained by the difference in bed level between the coarser Delft3D schematization and the more accurate vaklodingen data, see Figure 5.6.

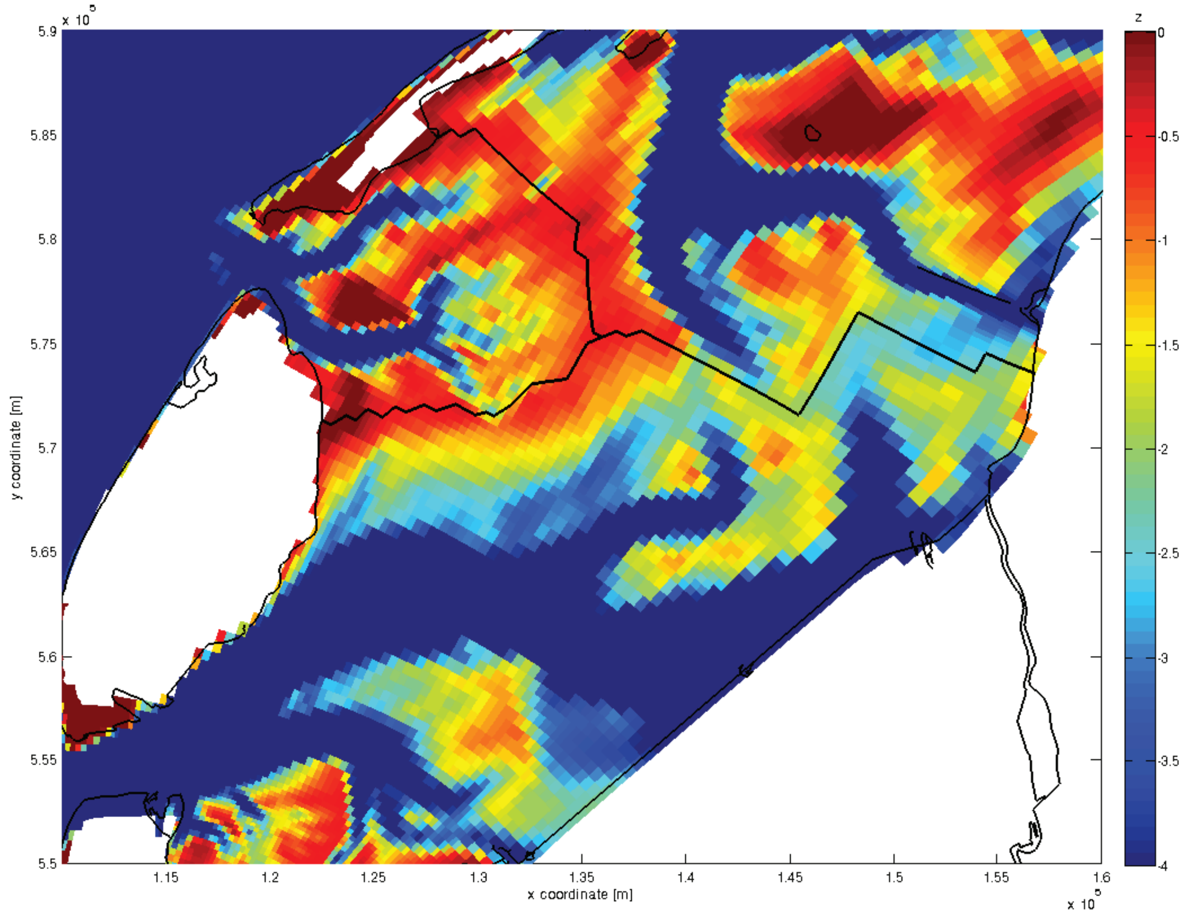


Figure 5.6 Delft3D bed level with corresponding hydraulic tidal divides for 2006

The hydraulic tidal divide between Marsdiep and Vlie seems to be located more to the north than the morphological tidal divide. This area is also influenced by the dredging of the navigation channel along the Pollendam, which counteracts the retreat of the branches of the Vlie channel system. From the position of the hydraulic and morphological tidal divide one can expect a further northward shift of the morphological tidal divide. In recent years the flats there have become higher, which is needed for equilibrium.

From equilibrium relations it is known that due to the closure of the Zuider Sea the Marsdiep basin is still far out of equilibrium regarding the amount of flat area. Because larger basins tend to have a less relative flat area then smaller basins, the increase of the basin surface area can help to reach the new equilibrium of the Marsdiep basin. A growing amount of flat area indicates that the basin is adapting towards a new equilibrium. The increase of the HW and LW levels however, result in a decrease of relative flat area (see Van Geer, 2007) in stead of an increase. Apparently, the adaptation of the Marsdiep basin has not been large and/or quick enough to compensate both the increased water levels and the closure of the Zuider Sea.

Remark: In Van Geer the basin boundaries seem to move more gradual to the present position, which is off course important for the amount of relative flat area in different years. This again shows the difficulty of/variability in marking the basin boundaries or hydraulic tidal divides.

Figure 5.7 and Figure 5.8 show a discrepancy between the hydraulic and morphological tidal divide in the eastern Wadden Sea. Again this is caused by the difference between the vaklodingen data and the Delft3D bed level schematization, which is especially behind Ameland very crude. This makes it different to draw conclusion regarding the position of the hydraulic and morphological tidal divides. The fact that the morphological tidal divides are relatively high, indicates that the basins are not far from equilibrium or at least that the tidal divides are moving only very gradual.

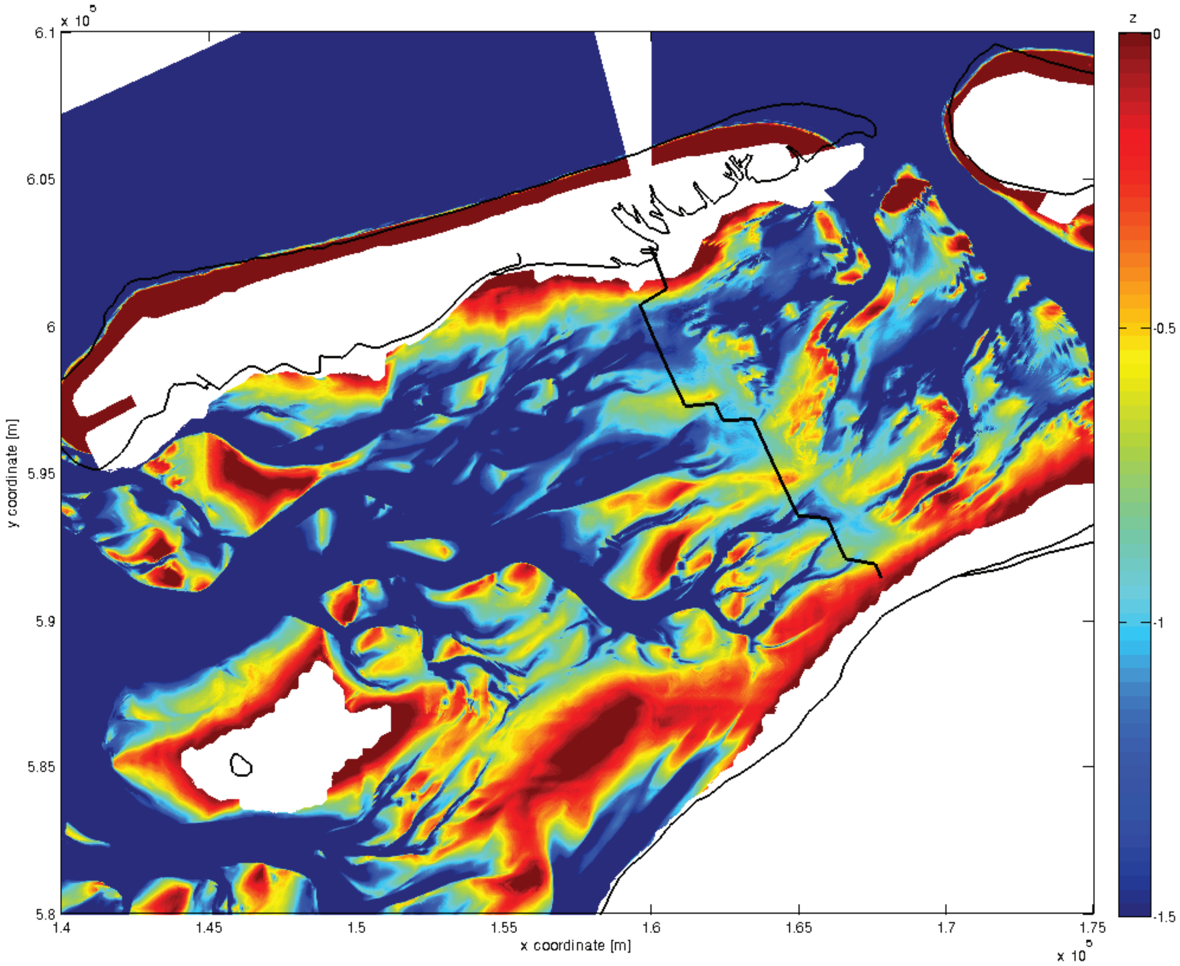


Figure 5.7 Bathymetry of 2003 behind Terschelling obtained from vaklodingen data and position of hydraulic tidal divide 2006

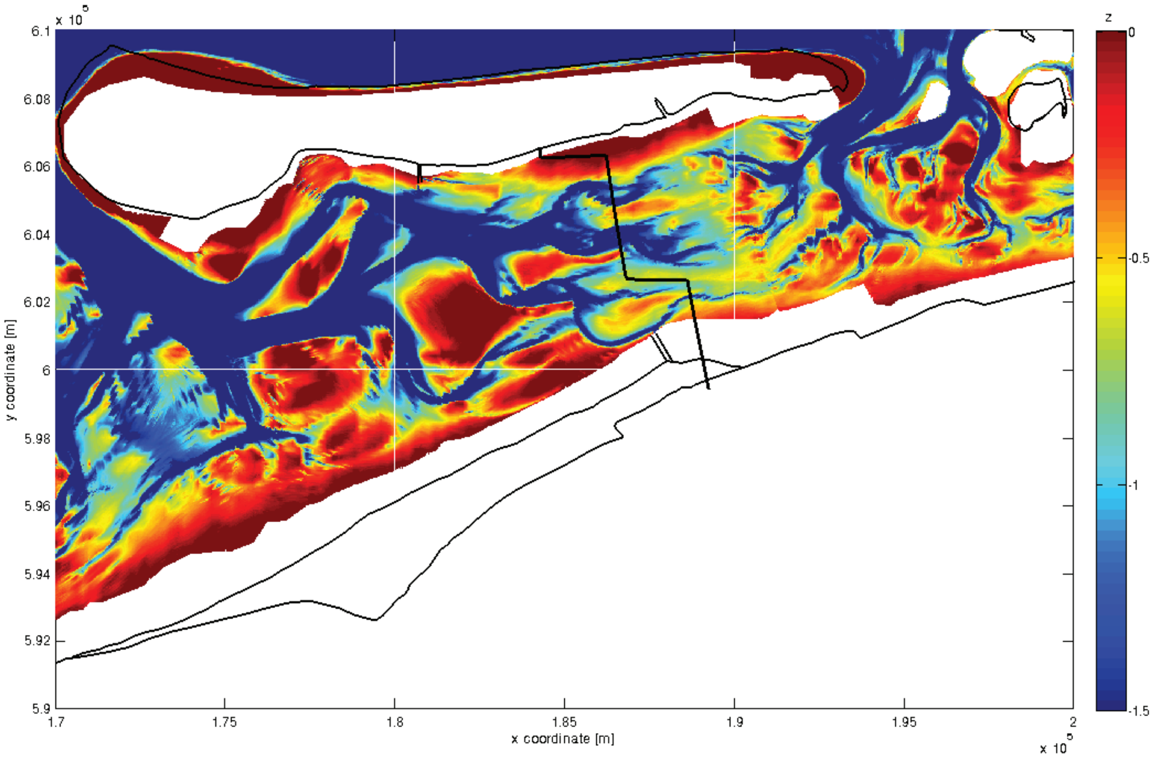


Figure 5.8 Bathymetry of 2003 behind Ameland obtained from vaklodingen data and position of hydraulic tidal divide 2006

5.4. Conclusions

Both the hydraulic and morphological tidal divides show an eastward movement in the period 1926-2006. The movement of the morphological tidal divide is generally slower than the hydraulic tidal divide, which is clearly illustrated by the morphological tidal divide between Marsdiep and Vlie. The hydraulic tidal divide made such a large shift here, that the morphological tidal divide could not follow it directly. For most other tidal divides the movement was smaller and the morphological tidal divide could follow more easily. This does not mean that the hydraulic tidal divide can move freely. It is bounded by the morphological tidal divide, which can keep the hydraulic tidal divide (temporarily) at a certain location. Changes in flow patterns as occurred after the closure of the Zuider Sea can erode morphological tidal divides and in this way remove the anchor for the hydraulic tidal divide. At certain moment, the morphological tidal divide has decreased in height so much, that the hydraulic tidal divide is not longer hindered in its movement. Hence, the bathymetry can be a large constraint in the position of the hydraulic tidal divide. This is not only the observation of the location of the hydraulic tidal divide near the Afsluitdijk in '1926', but is also confirmed by Dastgheib et al. (2008), who indicated the influence of the initial bathymetry on the long-term development of the Wadden Sea. This also implies that as long as the bathymetry is adjusting (morphological tidal divides are changing), the hydraulic tidal divide cannot be assumed to have a fixed position. When morphological tidal divides are moving, first a decrease in height is observed. When the morphological tidal divides are getting higher (compared to the water levels), this is an indication that it has reached its equilibrium location.

When the changes are more gradual, the morphological and hydraulic tidal divide do not differ much in position and the morphological tidal divide can keep up with the movement of the hydraulic tidal divide and stays at height.

The morphological tidal divides in the Wadden Sea show an increase in height. If this is also an increase relative to the water level has to be concluded from an analysis of water level changes. Van Geer (2007) investigated that the water levels in the Wadden Sea are also increasing. The present sea level rise amounts 17 cm/century (see Van Goor, 2001). The heightening of the morphological tidal divides is fragmented and therefore the exact heightening is difficult to determine. It can be stated that the heightening of the morphological tidal divide at some locations is larger than 17 cm/century and at some locations is smaller or equal than this value. For a final conclusion a more detailed study on this topic is needed, but in first instance the morphological seems to be heightening also compared to the increased sea level rise.

When comparing the position of the hydraulic and morphological tidal divides, the problem was the accuracy of the Delft3D bed level schematization. However, the main conclusion is that all hydraulic and morphological tidal divides considered are located more or less at the same position. The morphological tidal divide between Marsdiep and Vlie basin is still very low, and therefore these basins are believed to be still out of equilibrium. The other tidal divides might continue to move eastward, but this movement will be so gradual that the morphological tidal divide can easily keep up with this movement.

The tidal divide between Marsdiep and Vlie might also be influenced by the dredging along the Pollendam and this breakwater itself. Due to this, the hydraulic tidal divide will probably not move (a lot) further northward. The morphological tidal divide will heighten and might move slightly northward to get the same position as the hydraulic tidal divide.

6. Theory applied to Wadden Sea

The simplified channel case gave insight in the influence of the wave amplitude ratio and phase difference on the position of the tidal divide. It turned out that the bottom friction and depth are also very important parameters. Until now the Wadden Sea was mainly studied regarding the movement of tidal divides. In this chapter the coupling between the simplified channel case and the Wadden Sea is made. What is to be expected from the tidal divides in the Wadden Sea based on the theory of chapter 3?

6.1. Approach

In chapter 3, two basins were schematized to a rectangular channel and the position of the tidal divide was determined based on the channel geometry and the properties of the incoming waves. In reality it is harder to find the equilibrium position of the tidal divide, because the hydrodynamics will change the basin geometry and will affect the position of the hydraulic tidal divide again. For this analysis, in which the Wadden Sea will be investigated in a qualitative way, the analytical approach with linearized bottom friction will be used. The analysis in chapter 3 showed that this method can give a good first estimate of the general trends. However, the linearized bottom friction parameter has to be handled with care. Usually, the bottom friction parameter is used to calibrate model in such a way that the flow velocities are a good resemblance of the reality. Using it the other way around is a bit tricky.

In the past the tidal ranges have been subject to changes due to the closure of parts of the basin. The tidal ranges in the inlets might also increase in the future due to increasing sea level rise. Therefore the current tidal ranges will be taken as starting point and the effect of increased tidal ranges will be considered. Due to human interference, the barrier islands are defended and therefore their location is more or less fixed. This means that the channel length can be kept constant. The phase difference, which is governed by the tidal wave propagation in the North Sea and the barrier island length, can also be taken constant.

When the barrier islands have a fixed position, the width at the inlets can also be assumed constant. The width of the basin in length direction is increasing exponentially, see van Straaten & Kuenen (1957). This assumption reduces the width variation to two parameters: the width at the inlet and the width at the end of the channels. However, for a first approximation the width variation is left out of consideration. In chapter 3 it became clear that the widening of the channel mainly had an amplifying effect on the surface elevation and in this way fixates the tidal divide. Due to this the position of the tidal divide may even be defined on beforehand. But, the channel system is actually formed by the position of the tidal divide and the hydrodynamics is the basins. Both mechanisms stabilize each other in this way and can not be considered separately.

Regarding the basin depth, the situation is more complex. The water depth is determining the wave length and the degree in which the waves 'feel' the bottom: the water depth determines the relative importance of the bottom friction term. Also the flow velocities are governed by the water depth in combination with the wave amplitude. The depth is thus an important parameter, which is also has a large variation in space.

To get insight in the position of the hydraulic tidal divides in the Wadden Sea, the depth and bottom friction parameter σ are varied and the tidal range, phase difference and basin length are assumed to have a constant value.

6.2. Parameters

The tidal range and phase difference are determined using the Delft3D model of 2006. Approximate basin lengths are quickly estimated from a map[5]. Table 6.1 shows the tidal range for each inlet. The computed tidal range (column in the middle) is the average of all peaks minus the average of all falls in the period of one month. This tidal range is lower than the tidal ranges as computed by Elias. His tidal ranges are basin averaged values. In all basins the tidal range is higher in the basin than in the inlet, which is a result of the partially standing character of the tidal wave in the basin and the increasing cumulative width of the branches with larger distance from the inlet.

	Tidal range (inlet)	Tidal range Elias (basin averaged)
Marsdiep (MD)	1.24 m	1.65 m
Eierlandse Gat (EG)	1.50 m	1.65 m
Vlie Inlet (VI)	1.75 m	1.90 m
Borndiep (AI)	1.93 m	2.15 m
Pinkegat (PI)	2.03 m	
Zoutkamperlaag (ZL)	1.96 m	
Frisian Inlet (FI)	2.00 m	2.20 m

Table 6.1 Tidal range for all inlets

The phase difference is calculated between adjacent inlet gorges, see Table 6.2. Also the amplitude ratio is listed in the table. Also a rough estimation of the basin length is included, which is derived by measuring the distance between the consecutive inlets. This basin length is thus a minimum length. When the path of the existing branches is used, the length will be longer, but then the analysis is also more biased.

Tidal divide	Phase diff. [rad]	Amplitude ratio	L
MD-EG	0.19	1.21	26 km
EG-VI	0.12	1.17	23 km
MD-VI	0.31	1.41	49 km
VI-AI	0.17	1.10	33 km
AI-PI	0.16	1.05	27 km
AI-FI		1.04	34 km

Table 6.2 Phase difference, amplitude ratio and basin length

Assuming the tidal wave period, the tidal range and phase difference constant, the position of the tidal divide depending on the relative wave length and friction parameter σ can be derived. Both the wave length and the friction are defined by the water depth. The parameter σ iteratively depends on the flow velocity. This also implies that the channel should be divided in multiple blocks with more or less the same flow velocities, depth and value of σ. For each of these blocks, new value for *a* and φ should be derived. It is not necessary to do this to get insight in the tidal divides in the Wadden Sea, but it is good to realize that this would be the method to make a detailed calculation.

Although the parameter σ has a large variation over the basins, an order of magnitude can be derived. The parameter σ is defined by:

$$\sigma = \frac{8}{3\pi} c_f \frac{\hat{u}}{\omega R} \approx 24 \cdot \frac{\hat{u}}{h}$$

With:
c_f=0.004
ω=1.4*10^{-4} rad/s

A value 0.004 is taken for c_f, which is often used for a rectangular channel. Assuming that the flow velocities at the inlets are O(10^0) and the water depth is O(10^1), the value of sigma in the inlets is

[5] Google Earth.

$O(10^0)$. Moving away from the inlets, both the water depth and the velocities decrease. Due to this, the value of σ probably will not vary largely. However, a couple of values for σ will be considered, because it is already known that the position of the tidal divide is very sensitive to the value of σ.

The dimensionless parameter k_0L, which is the deep water wave number times the channel length, can be considered as a measure for the depth and the basin/channel length. With $k_0=\omega/c$ and $c=\sqrt{(gh)}$, the contribution of the water depth h to the frictionless wave number is given. Of course, friction will affect the wave length in the basins, resulting in a larger value for k compared to k_0. The position of the tidal divide will however be plotted versus the k_0L for various values of the friction parameter σ. The advantage of this is that the effect of the bottom friction is in only included via the parameter σ and not also via kL.

The large depths at the inlets result in large wave lengths. The frictionless wave number is $O(10^{-5})$ and the channel length is $O(10^4)$, hence k_0L is $O(10^{-1})$. Closer to the tidal divide, the basin is shallower and the wave length decreases, resulting in a larger wave number. The remaining channel length also decreases. But also close to the tidal divide, the tidal wave length is still very long, resulting in relatively small values of k0L ($\approx O(10^0)$, depending on the actual water depth and channel length (width of the morphological tidal divide).

6.3. Results

The parameters for the Wadden Sea result in the following figures, in which the vertical axis indicates the position of the hydraulic tidal divide and the horizontal axis is a measure for the depth and basin length. In the Wadden Sea, for a first indication can be assumed that the value of σ varies around 2 and the value of k_0L will not be much larger than 1.

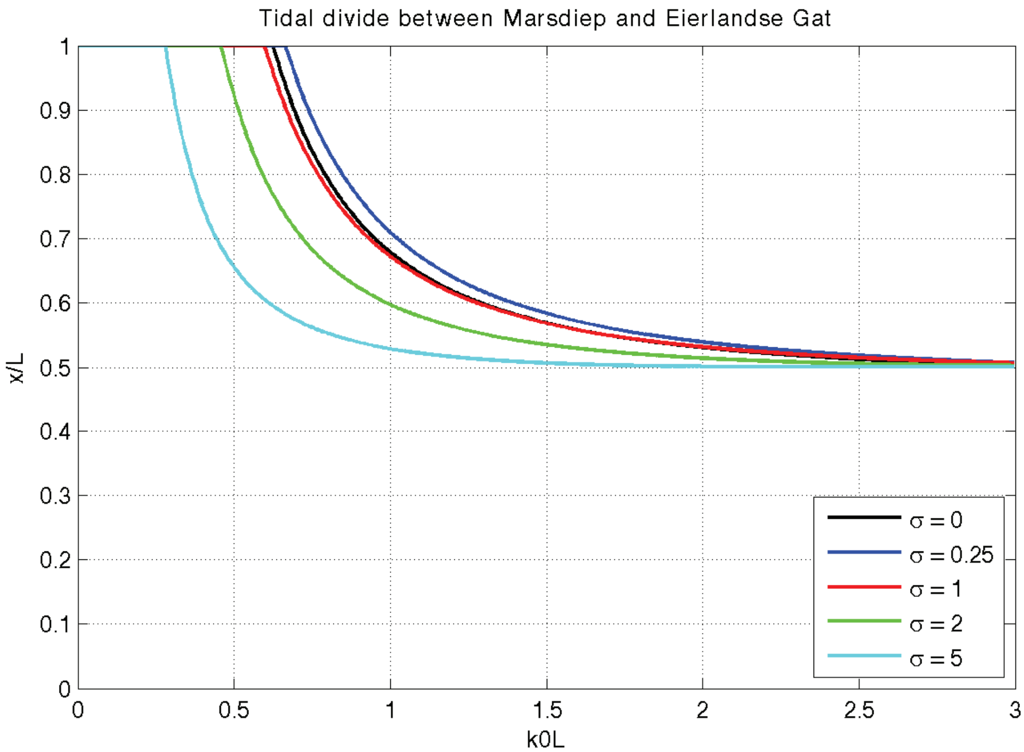


Figure 6.1 Tidal divide between Marsdiep and Eierlandse Gat, computation with *a*=1.21 and φ=0.19

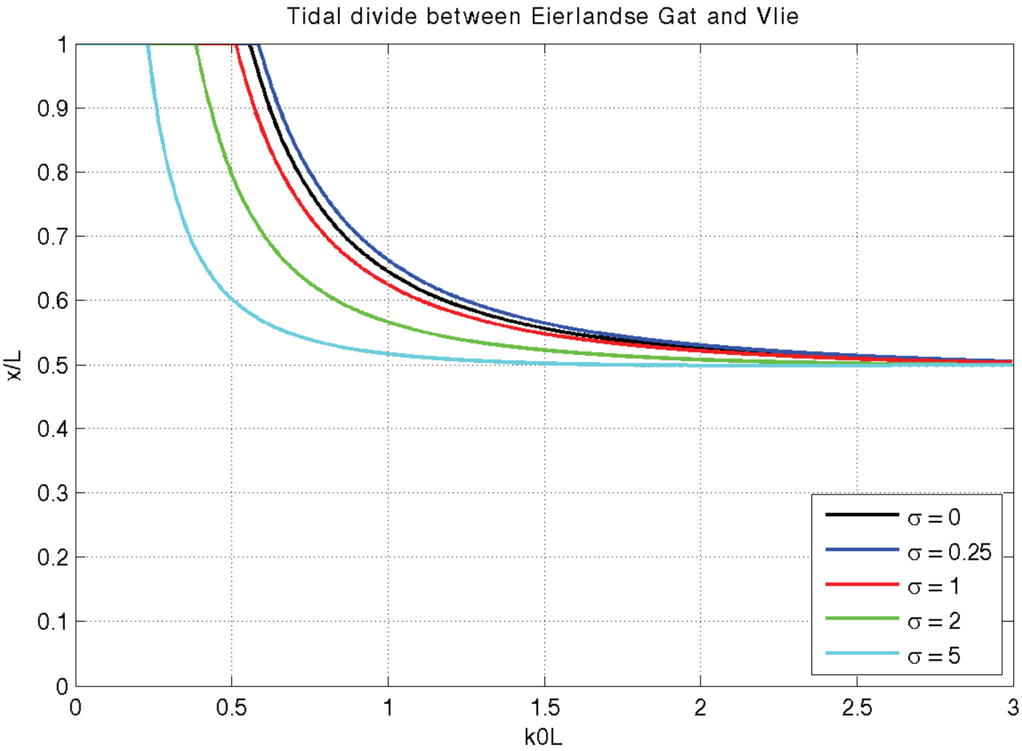


Figure 6.2 Tidal divide between Eierlandse Gat and Vlie, computation with *a*=1.17 and φ=0.12

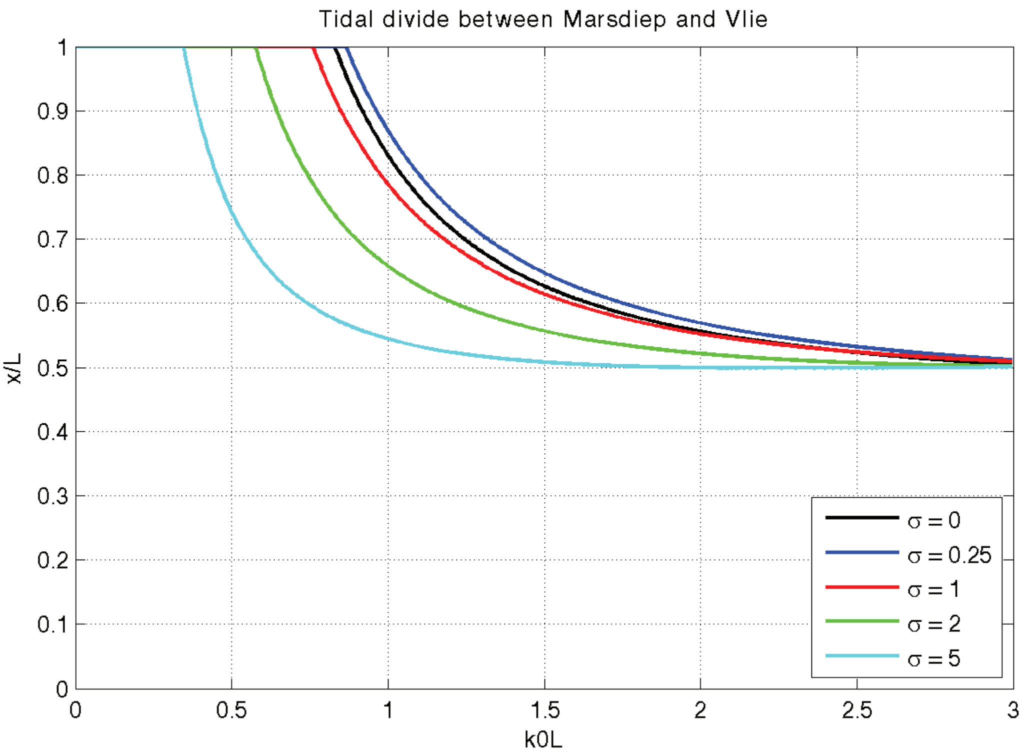


Figure 6.3 Tidal divide between Marsdiep and Vlie, computation with *a*=1.41 and φ=0.31

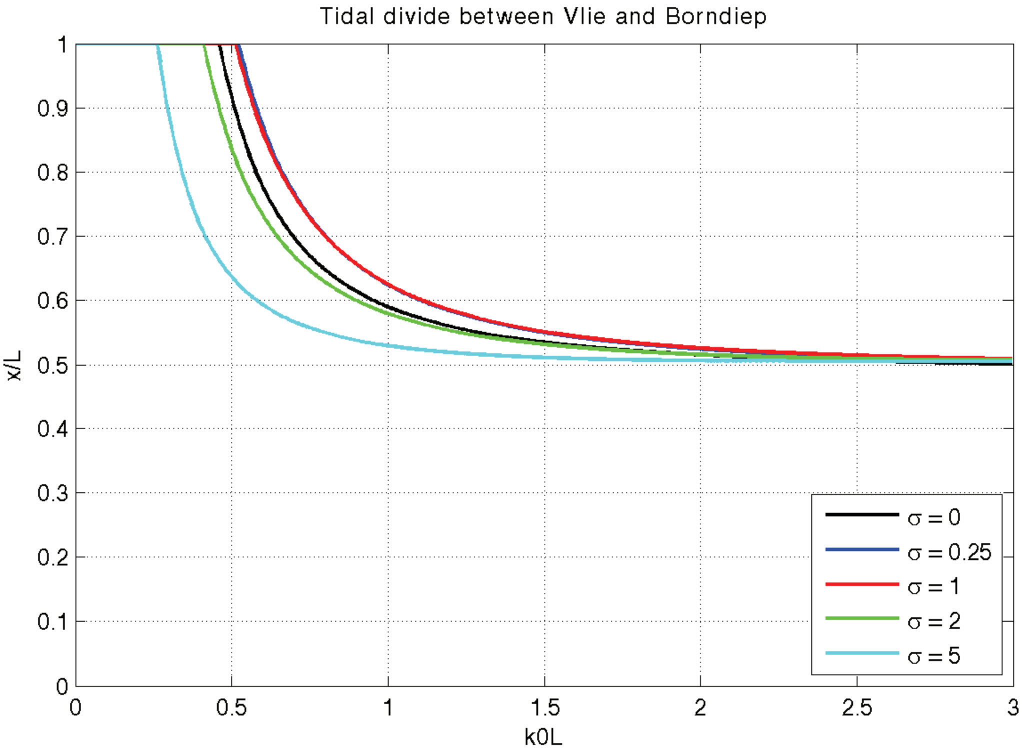


Figure 6.4 Tidal divide between Vlie and Borndiep, computation with *a*=1.1 and φ=0.17

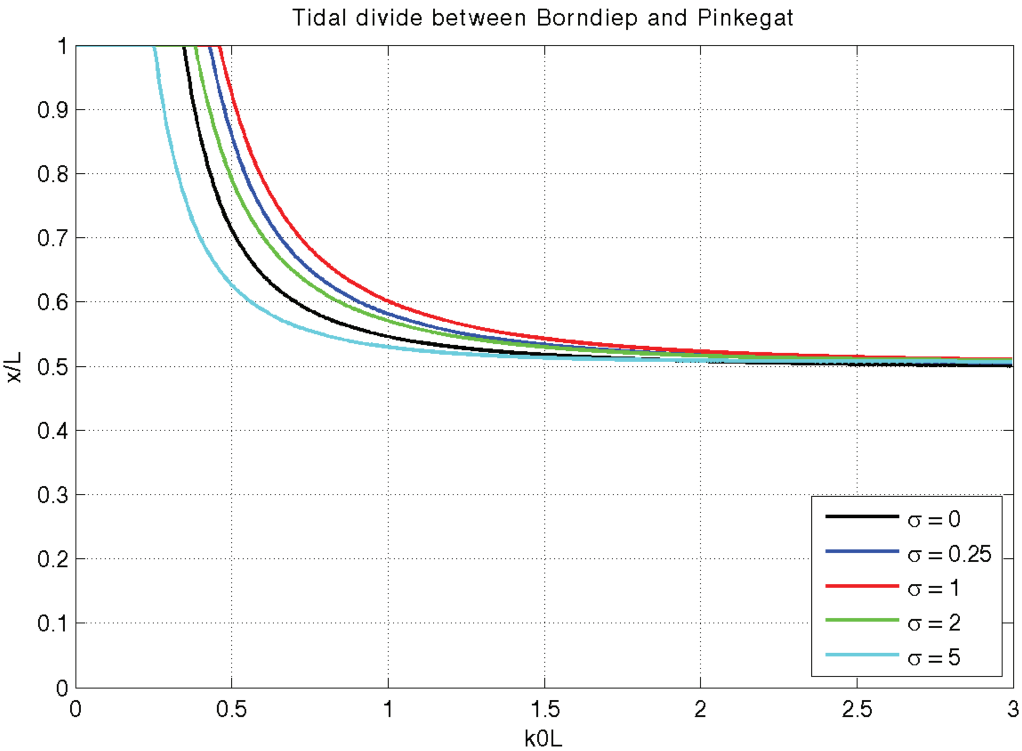


Figure 6.5 Tidal divide between Borndiep and Pinkegat, computation with *a*=1.05 and φ=0.16

With the order of magnitude of k_0L and σ which were derived for the inlets, no tidal divide can be present. This means that the basin must get shallower moving away from the inlet. In addition, it can be concluded that for the Wadden Sea it cannot be stated on beforehand that the position of the tidal divide will always be located halfway the channel. This means that the properties of the tidal wave do have a large influence on the position of the tidal divide.

For all tidal divides, a certain minimum depth and distance between the inlets has to be guaranteed in order to allow for a hydraulic tidal divide. This requirement is most severe in the western Wadden Sea, especially the tidal divides bordering Marsdiep have the need for the largest values of k_0L. The tidal divide between Marsdiep and Vlie has a relatively long channel length, but for the tidal divide between Marsdiep and Eierlandse Gat this implies that the basin should be relatively shallow.

The values of σ and k_0L in the inlets do not allow for a tidal divide. This points at the fact that the basins could only came into existence when a certain bathymetry and depth was present. Afterwards, the inlets eroded and became deeper. This can be confirmed by the long-term evolution as described in chapter 2.2. Next to this, it is already known that the initial conditions are determining the evolution of the basins to a large extend (Dastgheib et al, 2008). This was illustrated by the position of the hydraulic tidal divides versus the morphological tidal divides in chapter 5 as well and is confirmed by these figures for the Wadden Sea.

From previous studies it is known that the Marsdiep would have to become shallower in order to arrive at its equilibrium state. This would result in a larger value of kL, and probably the tidal divide will be located more towards the middle of the fictitious channel. This implies that the tidal divide between Marsdiep and Vlie would then shift back towards the Marsdiep inlet. However, if the width of the fictitious channel is also taken into consideration, the tidal divide might be kept at its position.

The Wadden Sea is also subject to increasing sea level rise. This will result in a larger water depth in the basins and an increased tidal range. It is difficult to predict what will happen to the tidal divide in this case. The amplitude ratio will not necessarily change when the tidal ranges increase. Because both the tidal ranges and the water depth increase, the effect on the flow velocities is also not known on beforehand. Hence, to investigate the effect of sea level rise on the position of the tidal divide, more detailed information on tidal ranges and water depths is needed.

7. Conclusions and recommendations

In this chapter, the conclusions are presented by answering the research questions. After the conclusions, some recommendations are listed, pointing at fields of further research.

7.1. Conclusions

What is a tidal divide?
A distinction between a hydraulic tidal divide and a morphological tidal divide is made.

The hydraulic tidal divide is the line splitting the basins in terms of drainage. A hydraulic tidal divide between adjacent basins can therefore be used as a basin boundary. The hydraulic tidal divide can be defined as the location with the smallest standard deviation of the flow velocity. Defining the hydraulic tidal divide by a line, which is needed to use the hydraulic tidal divide as a basin boundary, can be arbitrarily and has to be done with care.

The morphological tidal divide has the shape of a spine, and the centre line of this spine can be used as a line representation of the morphological tidal divide. This does not necessarily coincide with the highest point in the bed level. The morphological tidal divide is the footprint of the hydraulic tidal divide and indicates where the tidal divide is or has been. In this way the morphological tidal divide can be used to tell something about the equilibrium of the basins. Also the height of the morphological tidal divide is important for this equilibrium, as was already indicated by Van de Kreeke et al. (2008).

Under what conditions a hydraulic tidal divide can be present?
Whether a hydraulic tidal divide can be present depends on the amplitude of the tidal waves at each channel end, the phase difference between the waves, the basin geometry: length, width and depth, and the bottom friction. Configuration of these parameters can be such that there is no tidal divide at all.

The position of the tidal divide is located towards the inlet where the wave enters last or the tidal range is largest.

Based on the sensitivity to the variation of the phase difference and amplitude ratio, a distinction can be made between a linear case (without bottom friction and advective term and simplified continuity equation) and a nonlinear case, in which these terms are included and important. When the wave amplitude is very small compared to the water depth, the flow velocities are generally low and the linear case is being approached. The nonlinear case resembles the situation with higher wave amplitudes compared to the water depth and higher flow velocities.

In the linear case, the amplitude ratio is the most important parameter in determining the position of the tidal divide. The influence of the phase difference on the position of the tidal divide is small and for the case with equal wave amplitudes even nil.

In the nonlinear case, the inclusion of bottom friction results in a much larger influence of the phase difference and the effect of the amplitude ratio is very small. Increasing bottom friction initially results in a tidal divide that the located more towards the channel end where the wave enters last. For even larger values of the bottom friction, the tidal divide shifts back towards the middle of the channel, because the wave is dampened and gets a more standing character.

The depth is a very important parameter, because it determines the magnitude of the flow velocities and the way the waves feel the bottom and in this way the importance of the bottom friction. In reality, the flow velocities will decrease when the depth decreases and the effect is smaller.

Regarding the basin geometry, conclusions are based on simulations with the linear case. Increasing the channel length results in less strict limits for the wave amplitude ratio and phase difference. When the channel gets wider towards the middle of the channel, this can result in a higher surface elevation and a more standing character of the wave.

Linearization of the bottom friction term can resemble the general trends reasonable. Simulations with Sobek and Delft3D showed if the flow velocities have a large variation over the channel, the simulations with linearization of the bottom friction term perform poorer. In the latter case, the advective and extra continuity term also need to be included in the simulations.

Coupled to the Wadden Sea, the limits of the phase difference and wave amplitude ratio mean that the tidal divides in the Wadden Sea can only exist if the basins are relatively shallow and/or the barrier islands have a certain length.

How do tidal divides manifest themselves in the Dutch Wadden Sea?
Analysis of the hydraulic and morphological tidal divides in the Wadden Sea was already used to find a good definition of the tidal divide. For the hydraulic tidal divides it can be stated that the tidal divide between Marsdiep and Vlie has the largest averaged standard deviation. The exchange of water between these two basins is also very large, which is facilitated by the low morphological tidal divide. The other basins are bordered by hydraulic tidal divides with lower flow velocities.

The morphological tidal divides in the eastern Wadden Sea resemble the spine-shaped structure the best. The morphological tidal divide between Marsdiep and Vlie is lowest of all tidal divides.

Why do the hydraulic and morphological tidal divides between the basins move?
The hydraulic and morphological tidal divide can move in order to adapt to a new equilibrium. After a large interference in the basin(s), the hydraulic tidal divide adapts quickest and determines a new position, but is obstructed by the position of the morphological tidal divide. The morphological tidal divide first has to decrease in height by the increased flow velocities, then the hydraulic tidal divide can reach its new position and the morphological tidal divide can follow. When the tidal divides are moving more gradual, the morphological tidal divide can keep up with the movement of the hydraulic tidal divide.

The tidal divides in the Wadden Sea are all moving in eastward direction. The tidal divide between Marsdiep and Vlie show the largest changes. All morphological tidal divides have the tendency to become higher, probably also compared to the increased water levels due to sea level rise. To be able to draw a more specific conclusion on this topic, a more detailed analysis of the average heightening of the tidal divides and the increased water levels is needed.

The moving of the tidal divides results in a large surface area for Marsdiep and Eierlandse Gat. Vlie basin is getting smaller, while Borndiep has more a less a constant size.

7.2. Recommendations

The following recommendations are done to further investigate the behaviour of tidal divides:

- Further investigate the effect of the basin geometry on the position of the tidal divide, mainly the depth but also the width can have a large influence on the position of the tidal divide, as was shown with the linear case. This should be further investigated, at least also for the non-linear case.

- Study the effect of wind and waves on the position of the hydraulic and morphological tidal divide. Van Veen (1950) already indicated the importance of wind on the position of tidal divides, with the simplified case the influence of the wind relative to other variables can be investigated.

- The effect of the fresh water discharges near Kornwerderzand and the position of and dredging near the Pollendam can also be investigated to see if this influences the tidal divide between Marsdiep and Vlie.

- Couple the increasing sea level rise in the Wadden Sea to the changes of the morphological tidal divide. This will show whether the morphological tidal divides are also getting higher relative to the water level, or that the bed is only adapting to the sea level rise.

- Compare the properties of the sediment particles to the flow velocities at the tidal divides. This can give more insight in the development of the morphological tidal divides. An increased insight in the transport of fine sediments (mud and silt) is also needed to better model these transports and can be helpful to understand the development of morphological tidal divides and the sediment transport between the basins.

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APPENDICES

Appendix A Delft3D model

The model has been used with the following settings:

Domain			
	latitude		52 dec. deg.
	orientation		10 dec. deg.
	grid points	m-dir	212
		n-dir	124
Time frame			
	time step		1 min
Physical parameters			
	gravity		9.81 m/s^2
	water density		1000 kg/m^3
	Chézy-coefficient		63 m$^{1/2}$/s
	slip condition		free
	horizontal eddy viscosity		1 m^2/s
Numerical parameters			
	advection scheme		cyclic
	threshold depth		0.1 m

The time step of 1 minute is small enough not to exceed the Courant number limit of 10, which is a practical limit for accuracy.

The grid is displayed in the figure below.

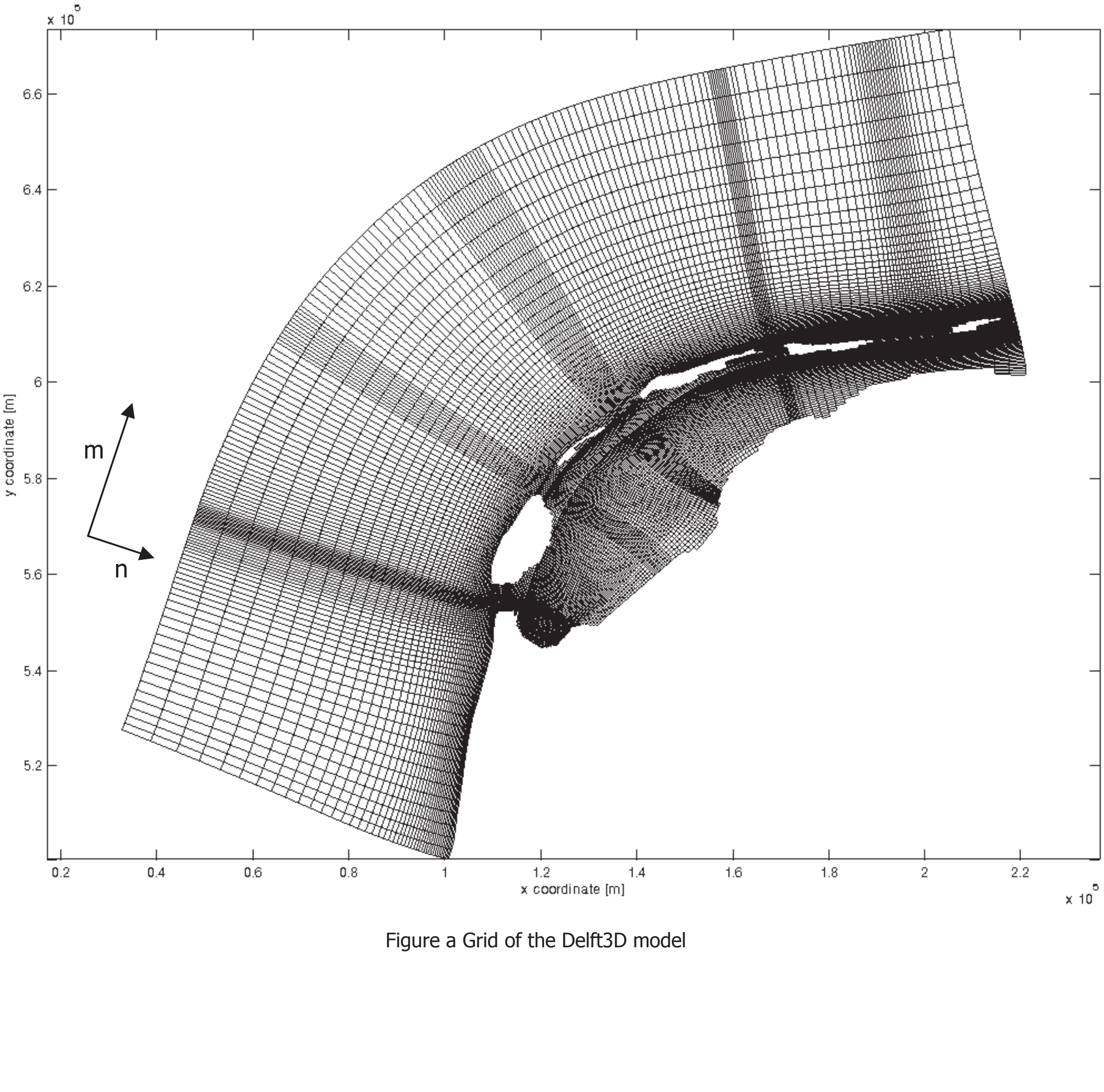


Figure a Grid of the Delft3D model

Appendix B Vaklodingen

The tables of the next page indicate which data have been used to represent the bathymetry of a certain year. The figures of the bathymetry are displayed in appendix D.

Ameland

box	year ‘2005’		year ‘1999’		year ‘1993’		year ‘1989’		year ‘1981’		year ‘1975’		year ‘1971’		year ‘1948’		year ‘1926’	
128_1312	11	07-03-‘05	9	01-03-‘99	7	01-03-‘93	6	01-05-‘89	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
128_1514	9	21-06-‘04	8	01-07-‘99	7	01-06-‘93	6	01-06-‘89	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
129_1514	12	07-03-‘05	11	01-07-‘99	10	01-07-‘93	9	01-06-‘89	8	‘81	7	‘75	6	‘71	3	‘48	1	‘26
129_1312	21 22	07-03-‘05 17-03-‘05	18 19	01-03-‘99 07-03-‘00	14	01-07-‘93	13	01-06-‘89	11 12	‘81 ’82	9	‘75	7 8	‘70 ’71	3 4	’48 ’49	1 2	’26 ’27
130_1312	16 17	08-03-‘05 17-03-‘05	13 14	01-03-‘99 07-03-‘00	11	01-03-‘94	9	01-04-‘87	8	‘82	6	‘75	5	‘70	2	‘49	1	‘27

Schiermonnikoog

box	year ‘2006’		year ‘2000’		year ‘1994’		year ‘1989’		year ‘1979’		year ‘1975’		year ‘1970’		year ‘1958’		year ‘1927’	
131_1312	15	16-01-06	13	07-03-00	11	01-03-94	9	01-04-87	7	‘79	6	‘75	5	‘70	3	‘58	1	‘27
132_1312	13 14 15	27-03-02 16-01-06 03-02-06	12	07-03-00	11	01-06-94	9 10	01-10-87 01-06-89	7	‘79	6	‘75	5	‘70	3	‘58	1	‘27
133_1312	13 14 15	01-01-05 03-02-06 07-02-06	11	07-03-00	9	01-11-94	7	01-06-89	6	‘79	5	‘75	4	‘70	2	‘58	1	‘27
131_1110	16	17-03-05	13	07-03-00	11	01-05-94	9	01-06-87	7	‘79	6	‘75	5	‘70	3	‘58	1	‘27
132_1110	18	15-04-06	14	07-03-00	12	01-05-94	9	01-04-87	7	‘79	6	‘75	5	‘70	3	‘58	1	‘27
133_1110	27	01-01-05	23	07-03-00	18	01-05-94	12	01-04-89	5	‘79	4	‘75	3	‘70	2	‘58	1	‘27

Terschelling

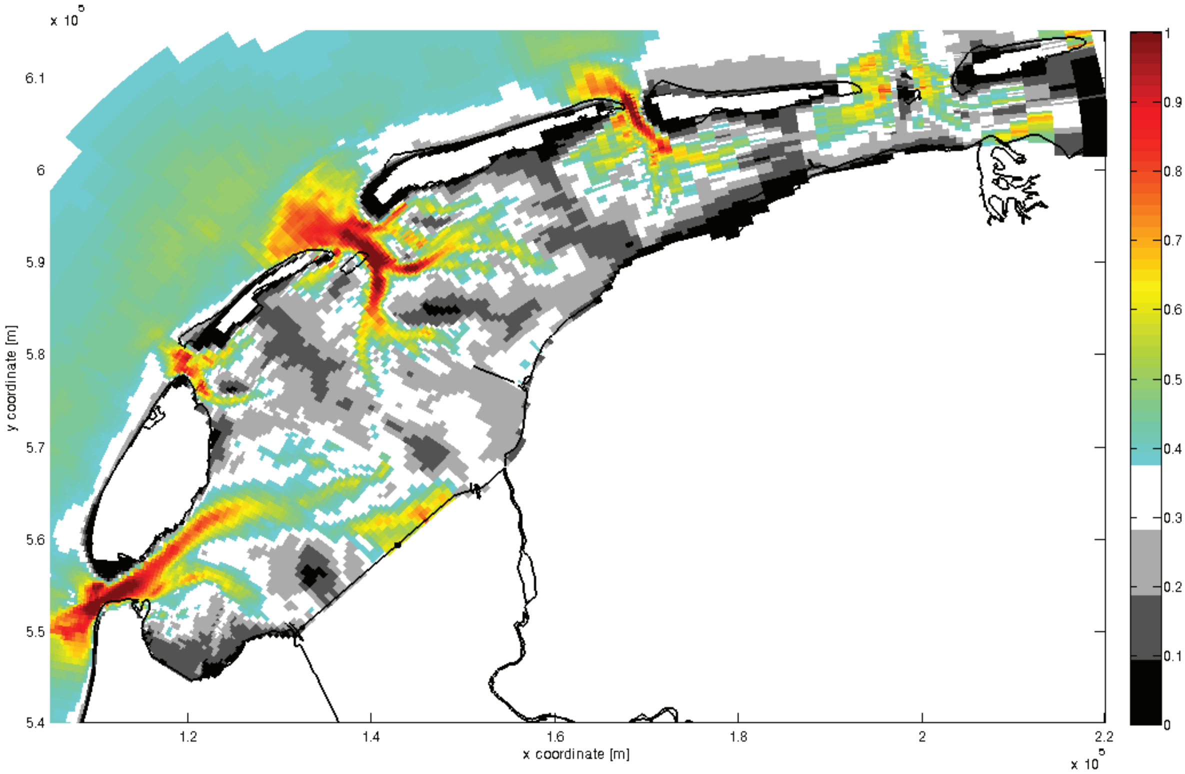
box	year ‘2010’		year ‘2004’		year ‘1998’		year ‘1992’		year ‘1988’		year ‘1981’		year ‘1975’		year ‘1971’		year ‘1948’		year ‘1926’	
125_1514	12	01-01-‘10	11	11-02-‘04	9	01-03-‘98	7	01-04-‘92	6	01-06-‘88	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
126_1514	11	01-01-‘10	10	11-02-‘04	9	01-05-‘98	7 8	01-08-‘91 01-07-‘93	6	01-01-‘88	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
127_1514	14	01-01-‘10	12 13	11-02-‘04 25-05-‘04	10 11	01-07-‘98 01-07-‘99	8 9	01-08-‘92 01-07-‘93	6 7	01-08-‘88 01-06-‘89	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
128_1514			9	21-06-‘04	8	01-07-‘99	7	01-06-‘93	6	01-06-‘89	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
125_1312	11	01-01-‘10	10	25-03-‘04	8	01-03-‘98	6	01-04-‘92	5	01-11-‘88	4	‘81	3	‘75	2	‘71	x		1	‘26
126_1312	15	01-01-‘10	13	11-02-‘04	10	01-04-‘98	7 8	01-04-‘92 01-02-‘93	6	01-08-‘88	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26
127_1312	14	01-01-‘10	12 13	25-03-‘04 25-05-‘04	9 10	01-04-‘98 01-03-‘99	7	01-03-‘93	6	01-05-‘89	5	‘81	4	‘75	3	‘71	2	‘48	1	‘26

128_1312			11	07-03-'05	9	01-03-'99	7	01-03-'93	6	01-05-'89	5	'81	4	'75	3	'71	2	'48	1	'26
125_1716	11	01-01-'10	9	01-07-'03	8	01-05-'98	7	01-05-'91	6	01-03-'88	5	'81	4	'75	3	'71	2	'48	1	'26
126_1716	12	01-01-'10	10	01-07-'03	9	01-07-'98	8	01-07-'91	7	01-06-'88	5	'81	4	'75	3	'71	2	'48	1	'26
127_1716	10	01-01-'10	9	01-07-'03	8	01-07-'98	7	01-08-'92	6	01-07-'88	5	'81	4	'75	3	'71	2	'48	1	'26

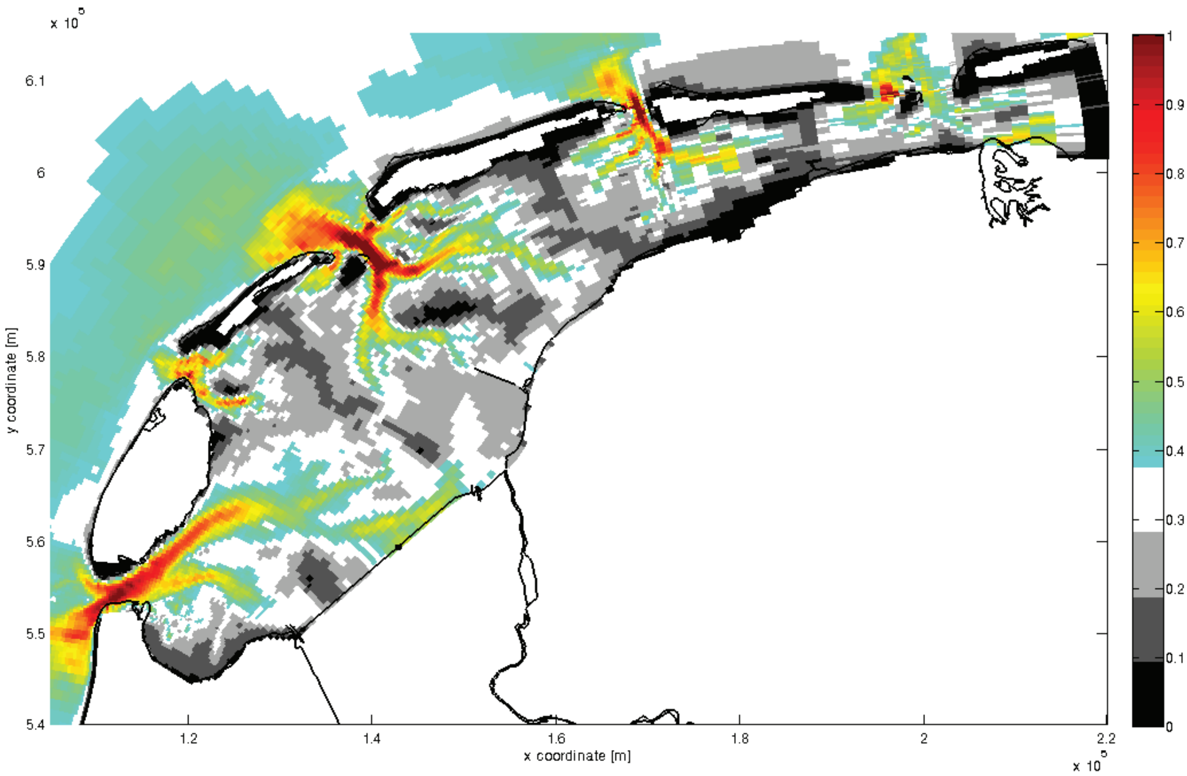
West

box	year '2009'		year '2003'		year '1998'		year '1991'		year '1981'		year '1975'		year '1971'		year '1948'		year '1926'	
125_1918	12	01-01-'09	11	16-04-'03	9 10	01-06-'97 01-06-'98	7 8	01-07-'91 01-08-'91	5	'81	4	'75	3	'71	2	'48	1	'26
125_1716	10 11	01-01-'09 01-01-'10	9	01-07-'03	8	01-05-'98	7	01-05-'91	5	'81	4	'75	3	'71	2	'48	1	'26
126_1716	11 12	01-01-'09 01-01-'10	10	01-07-'03	9	01-07-'98	8	01-07-'91	5	'81	4	'75	3	'71	2	'48	1	'26
126_1918	11	01-01-'09	10	01-07-'03	8 9	01-06-'97 01-07-'98	6 7	01-07-'91 01-09-'91	5	'81	4	'75	3	'71	2	'48	1	'26
124_1716	15 16	01-01-'09 01-01-'10	12 13 14	07-08-'02 14-01-'03 02-07-'03	10 11	01-05-'98 01-04-'99	8 9	01-07-'91 01-03-'93	5	'81	4	'75	3	'71	2	'48	1	'26
123_1716	16 17	01-01-'09 01-01-'10	14	14-01-'03	11	01-01-'99	8 9	01-04-'92 01-01-'93	5	'81	4	'75	3	'71	2	'48	1	'26
123_1918	14	01-01-'09	12 13	13-01-'03 14-01-'03	10 11	01-04-'97 01-03-'99	8 9	01-06-'91 01-05-'93	5	'81	4	'75	3	'71	2	'48	1	'26
124_1918	16	01-01-'09	14 15	14-01-'03 22-01-'03	11	01-06-'97	8 9 10	01-08-'91 01-09-'91 01-05-'93	5	'81	4	'75	3	'71	2	'48	1	'26
125_2120	11	01-01-'09	10	02-07-'03	9	01-08-'97	8	01-10-'91	5	'81	4	'75	3	'71	2	'48	1	'26
124_2120	11	01-01-'09	10	27-01-'03	9	01-04-'97	8	01-05-'91	5	'81	4	'75	3	'71	2	'48	1	'26
123_2120	11	01-01-'09	10	27-01-'03	9	01-04-'97	8	01-04-'91	5	'81	4	'75	3	'71	2	'48	1	'26
122_2120	15	01-01-'09	13	05-03-'01	11	01-03-'97	8 9	01-04-'90 01-03-'91	5	'81	4	'75	3	'71	2	'48	1	'26
122_2322	12	01-01-'09	11	05-03-'01	10	15-05-'99	8	01-06-'91	5	'81	4	'75	3	'71	2	'48	1	'26
123_2322	10	01-01-'09	9	13-03-'03	8	01-09-'97	7	01-06-'91	5	'81	4	'75	3	'71	2	'48	1	'26
124_1514	13	01-01-'10	12	07-08-'02	9	01-03-'98	7	01-03-'92	5	'81	4	'75	3	'71	2	'48	1	'26

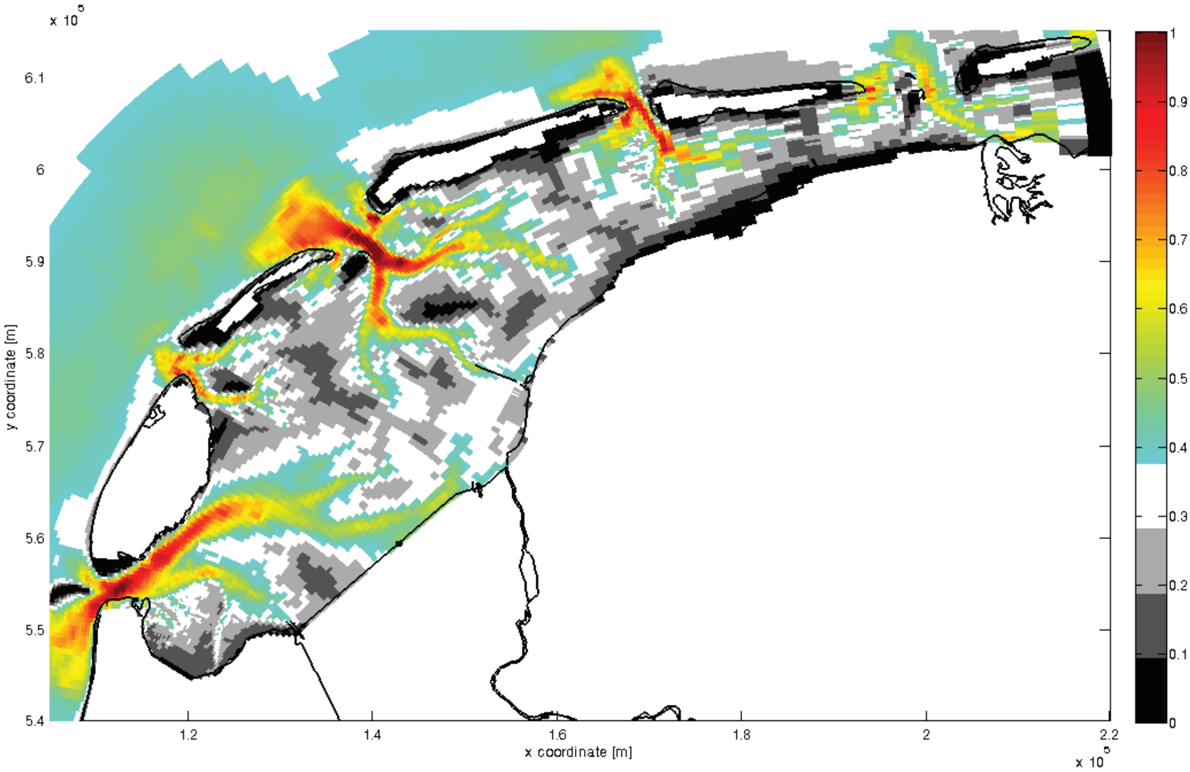
Appendix C Hydraulic tidal divides



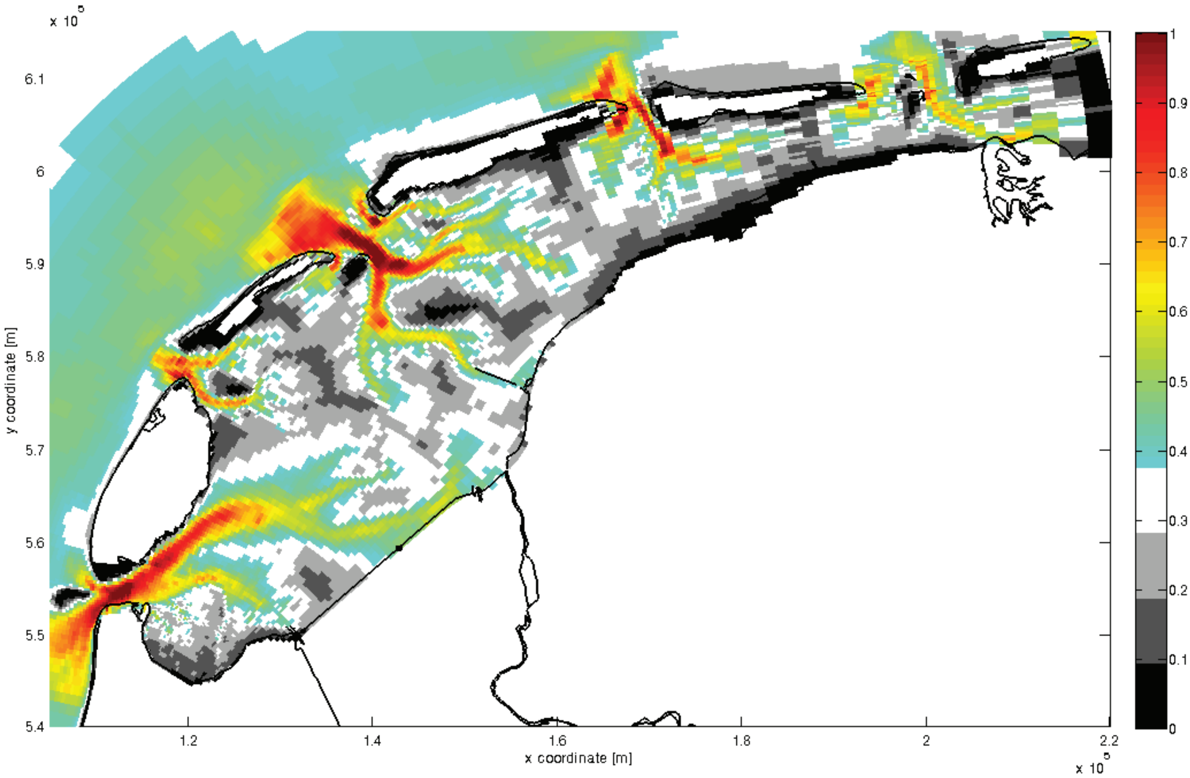
1926



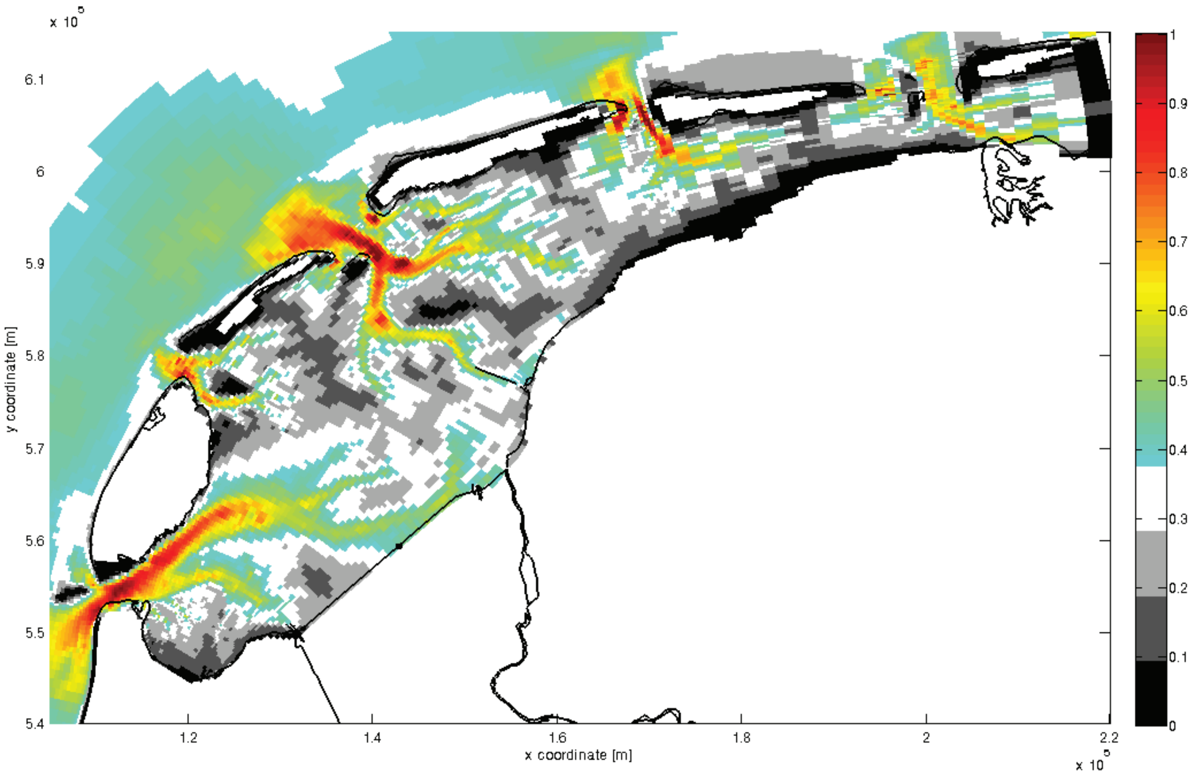
1948

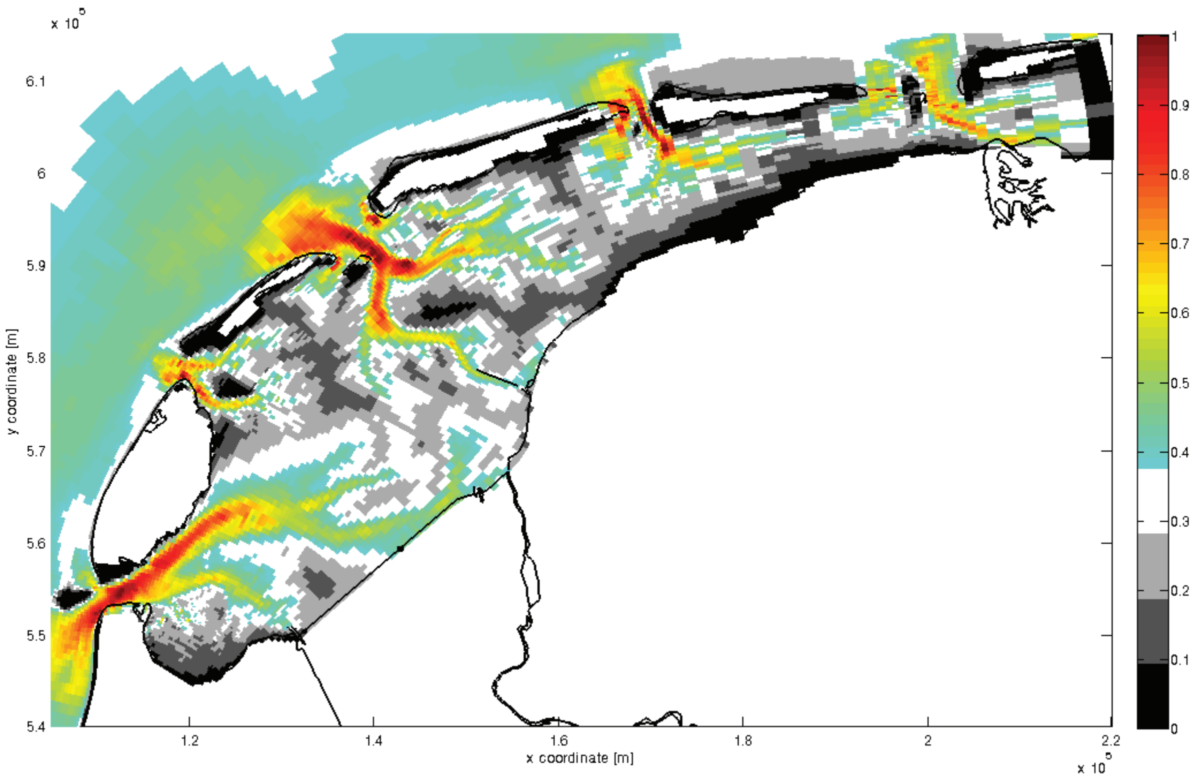

x 10^5
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
y coordinate [m]
1.2
1.4
1.6
1.8
2
2.2
x coordinate [m]
x 10^5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

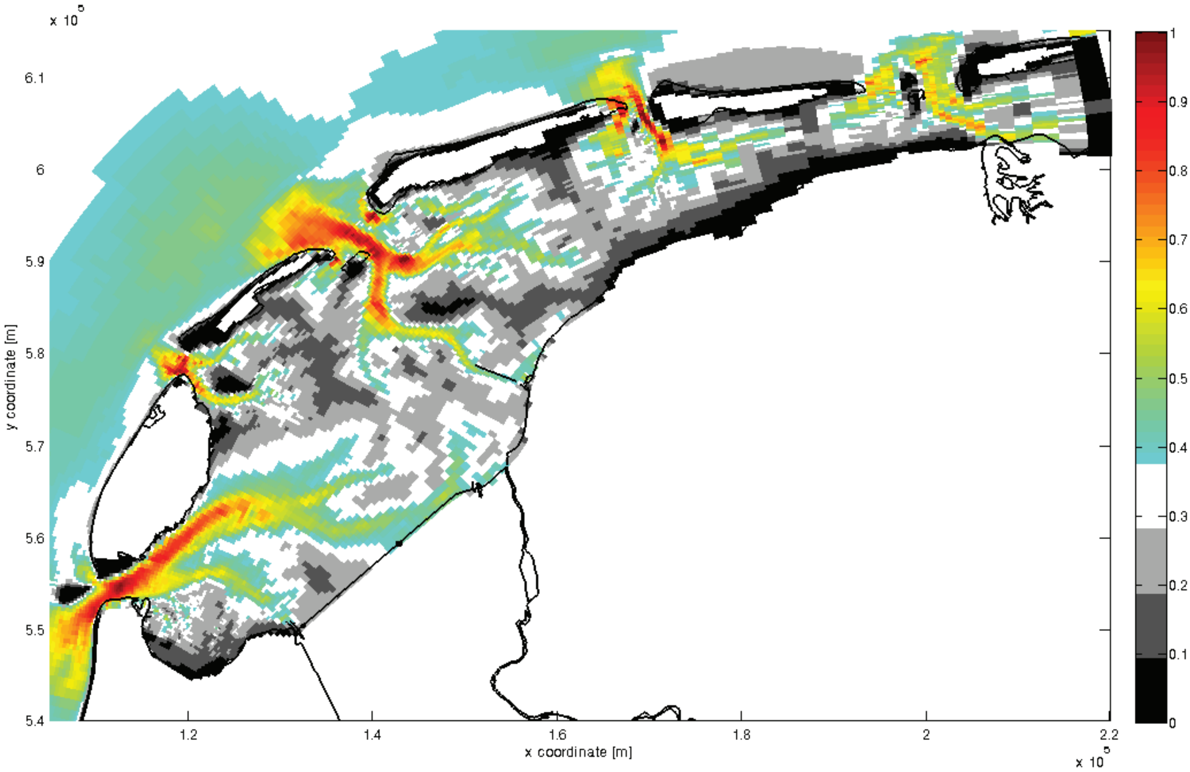
1975


x 10^5
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
y coordinate [m]
1.2
1.4
1.6
1.8
2
2.2
x coordinate [m]
x 10^5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

1981

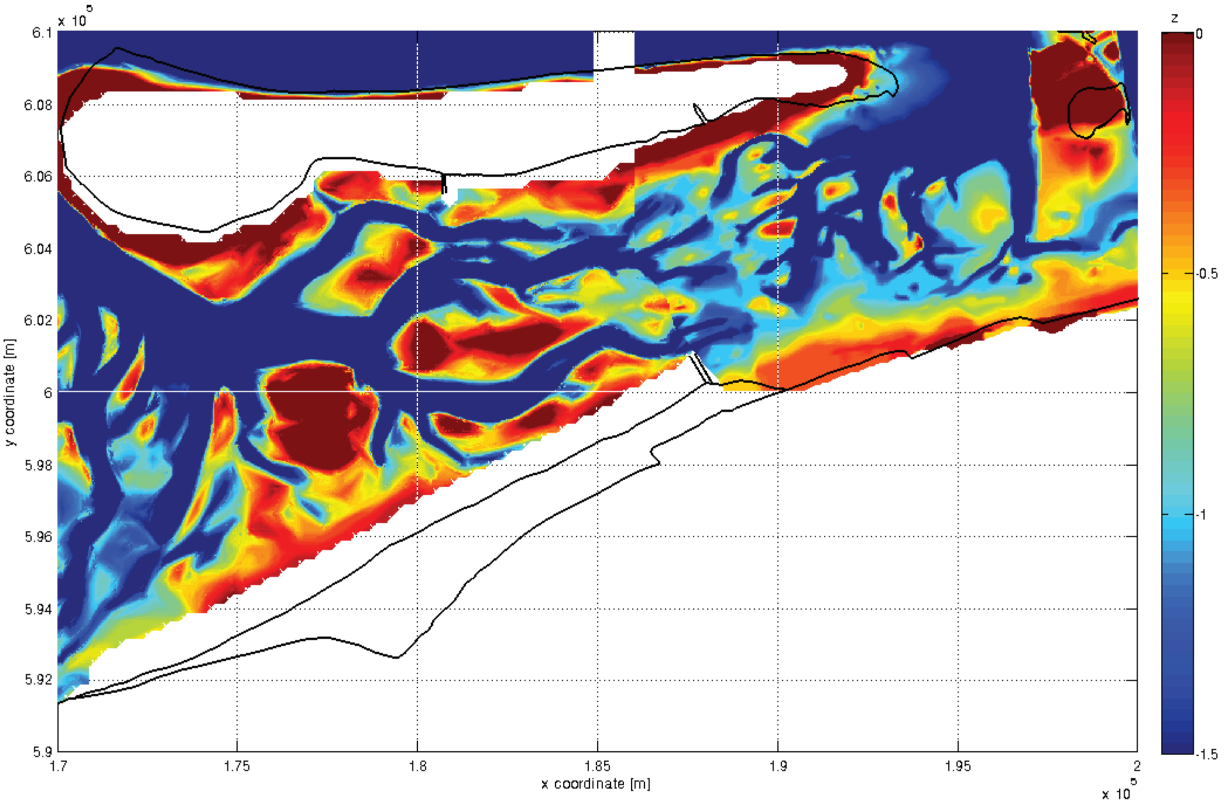

x 10^5
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
y coordinate [m]
1.2
1.4
1.6
1.8
2
2.2
x coordinate [m]
x 10^5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1991


x 10^5
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
y coordinate [m]
1.2
1.4
1.6
1.8
2
2.2
x coordinate [m]
x 10^5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1998

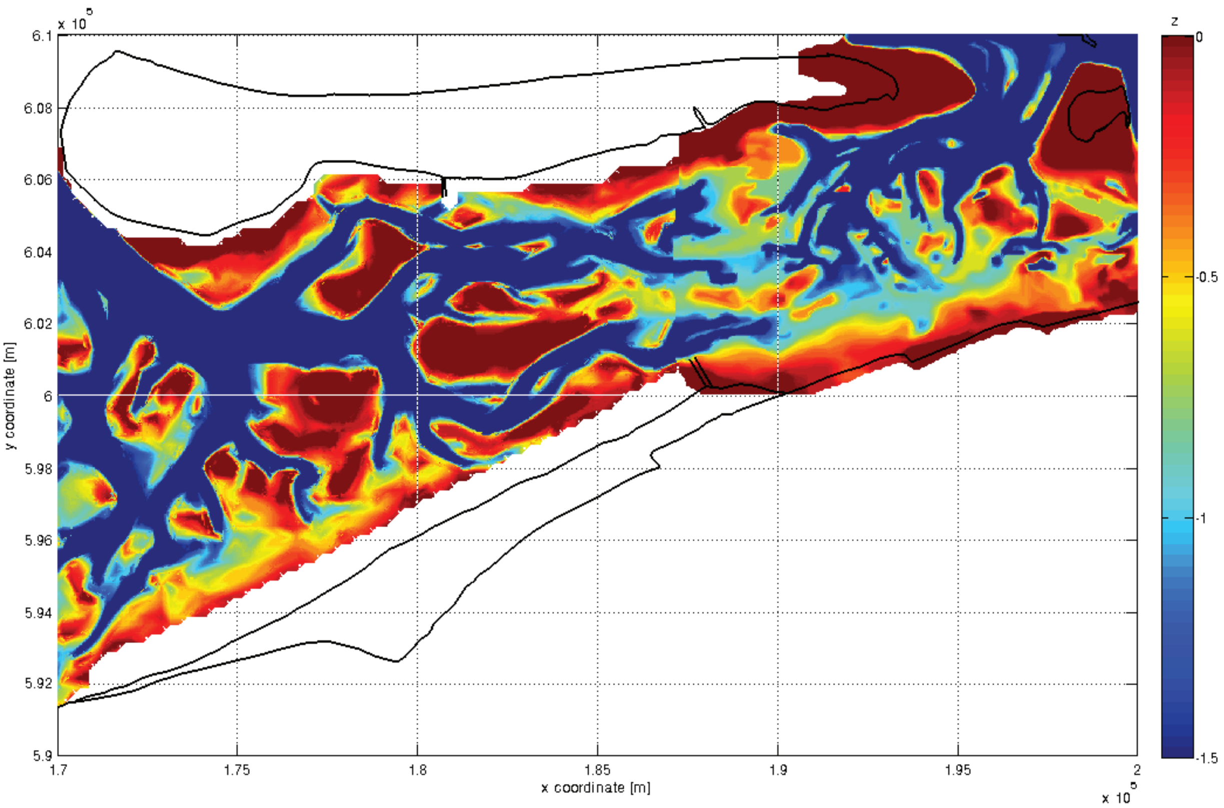

x 10^5
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
y coordinate [m]
1.2
1.4
1.6
1.8
2
2.2
x coordinate [m]
x 10^5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

2006

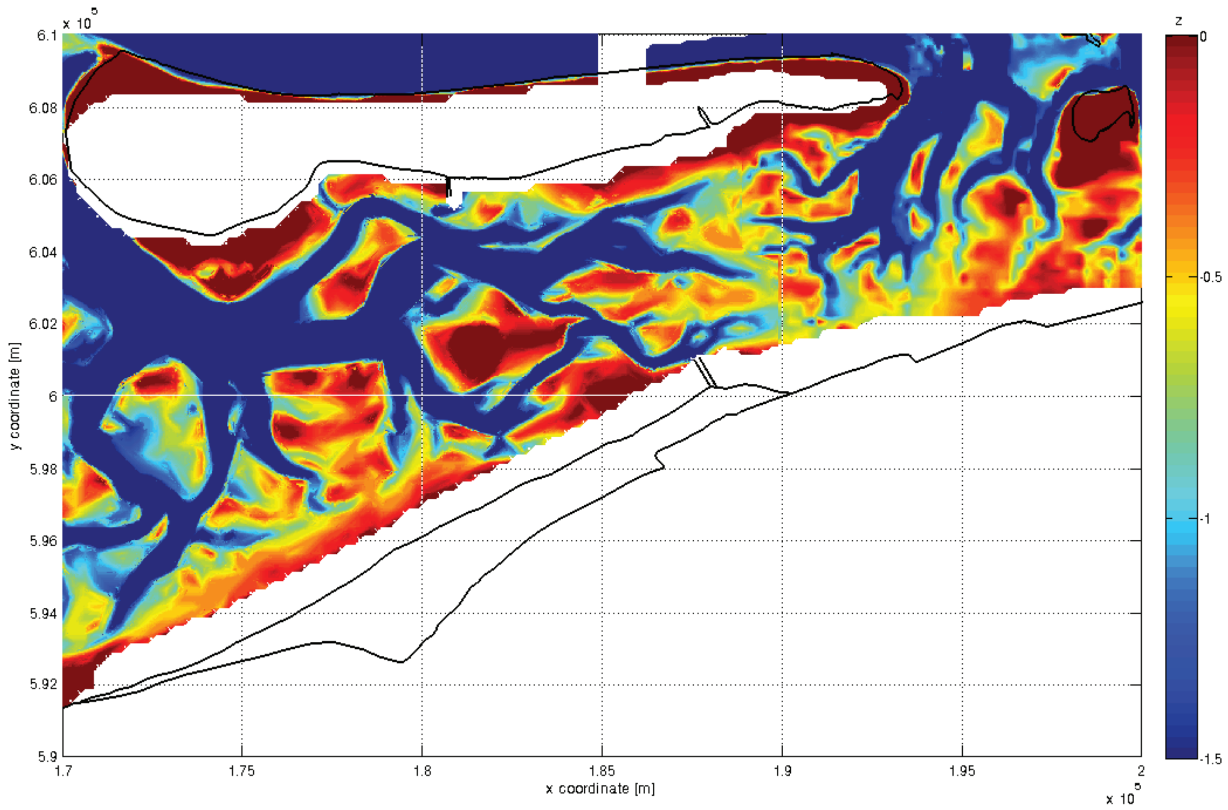
Appendix D Morphological tidal divides



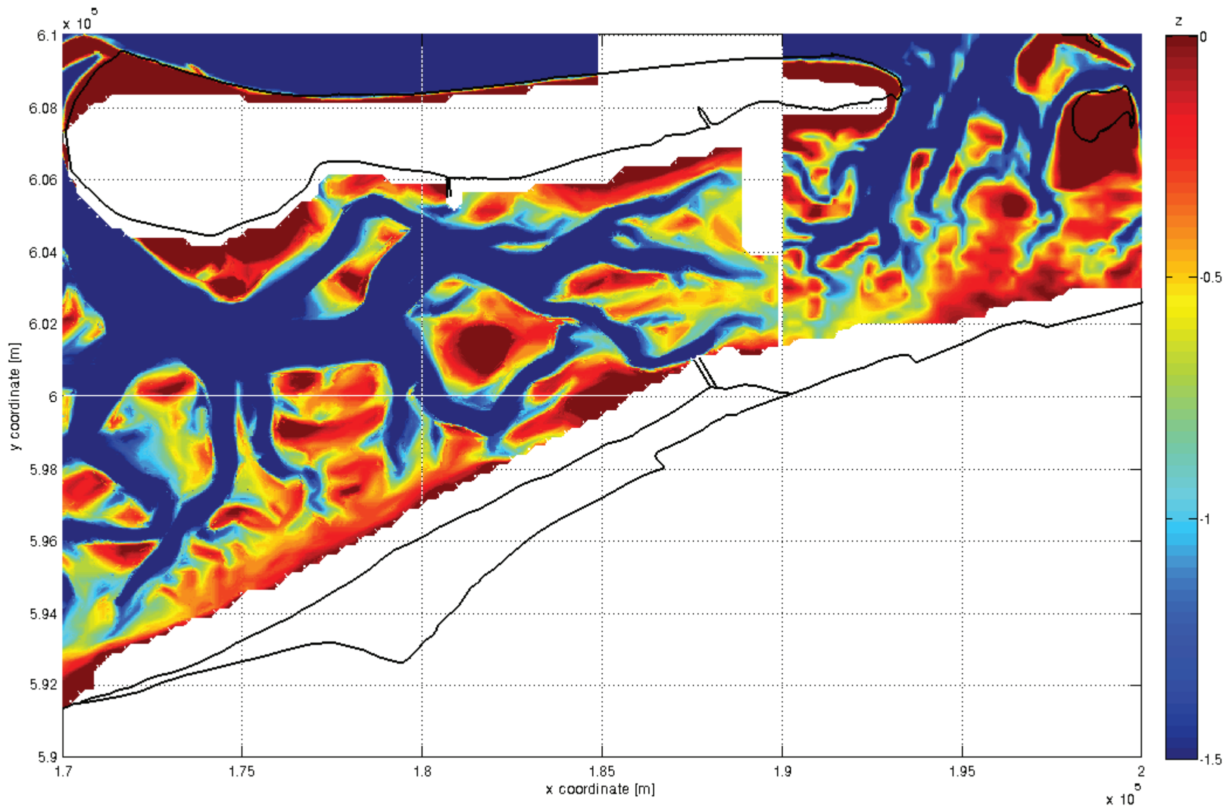
Ameland 1926



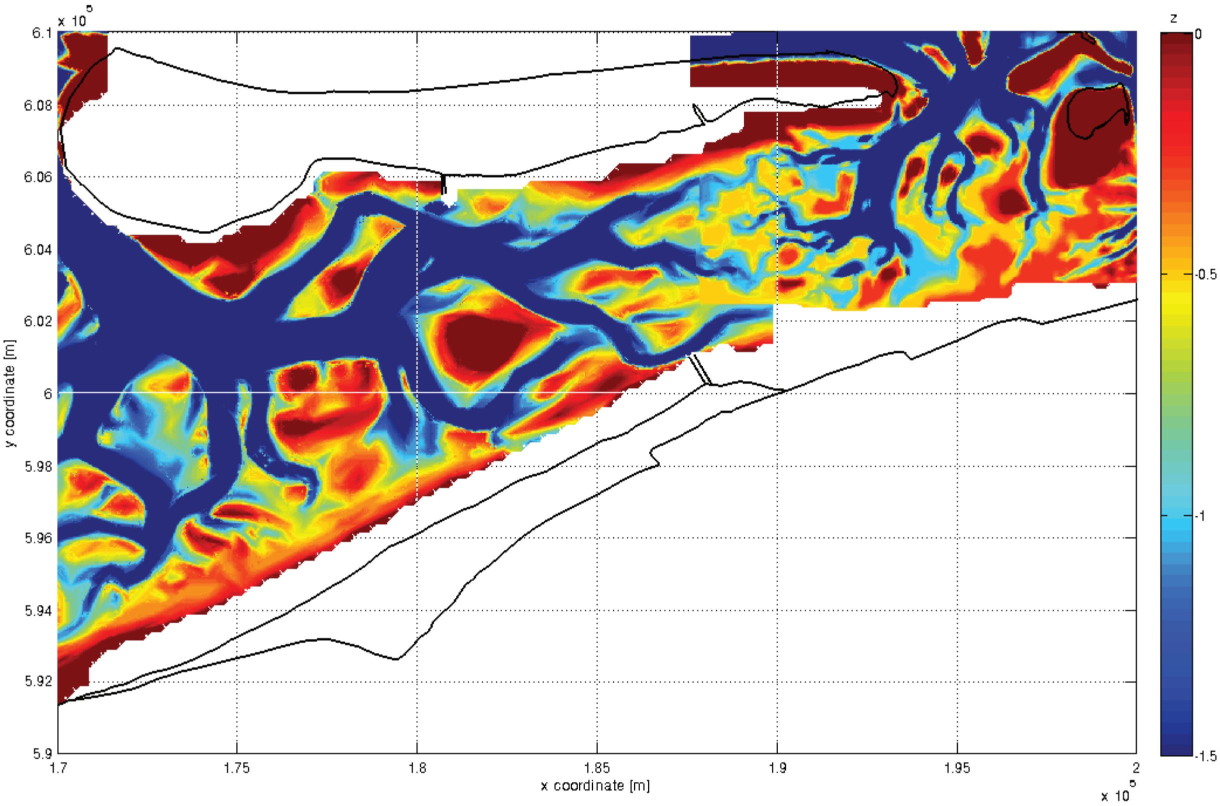
Ameland 1948



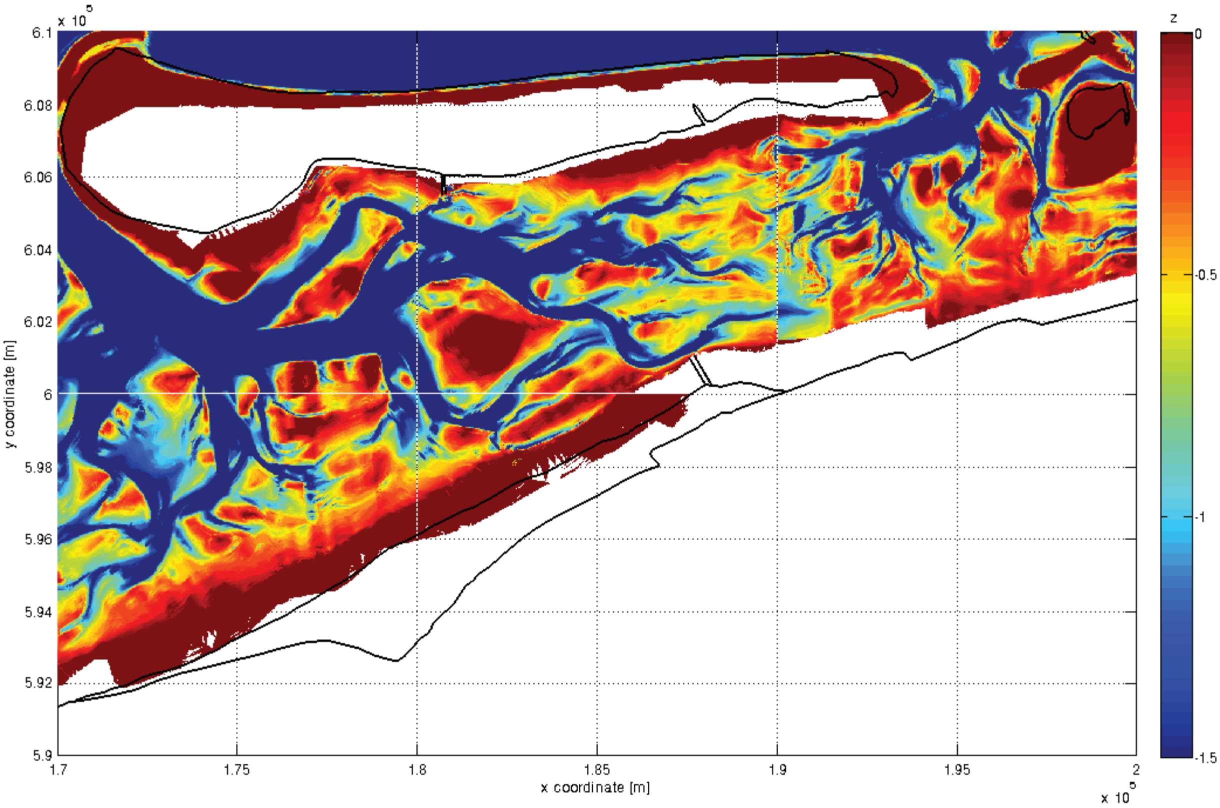
Ameland 1971



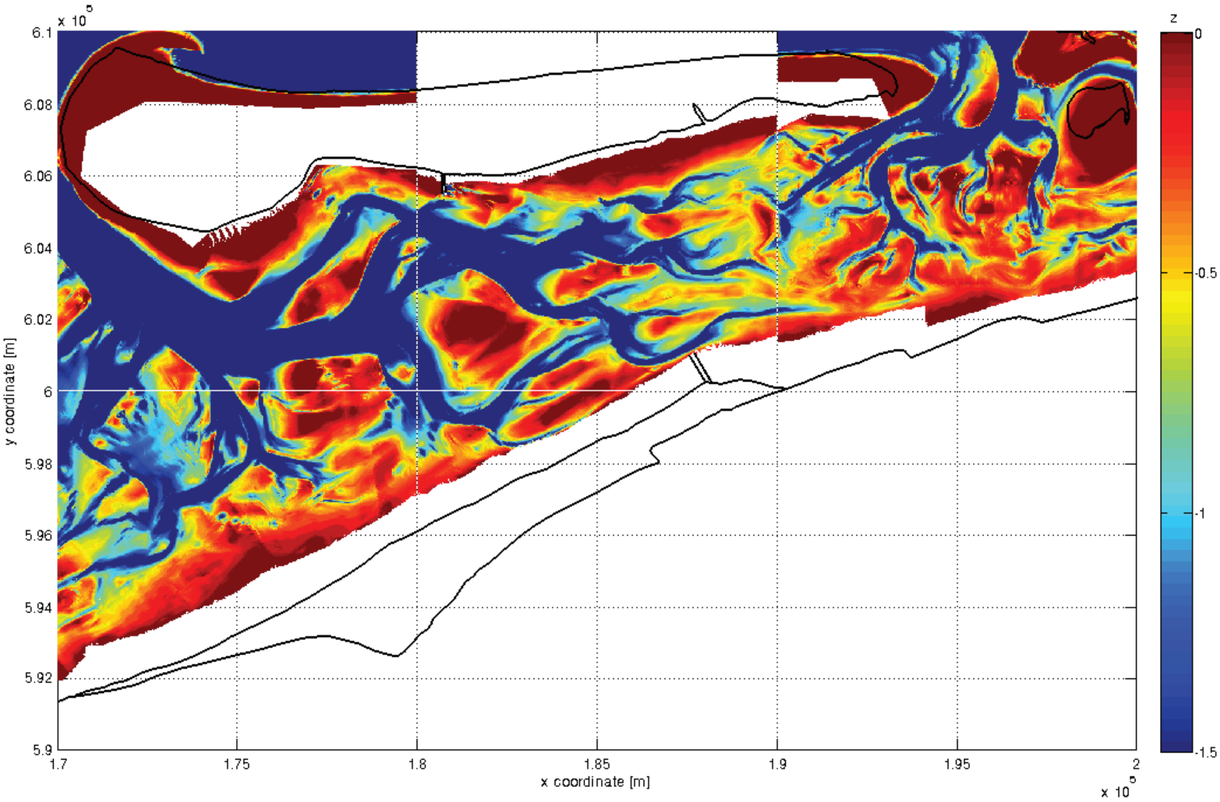
Ameland 1975



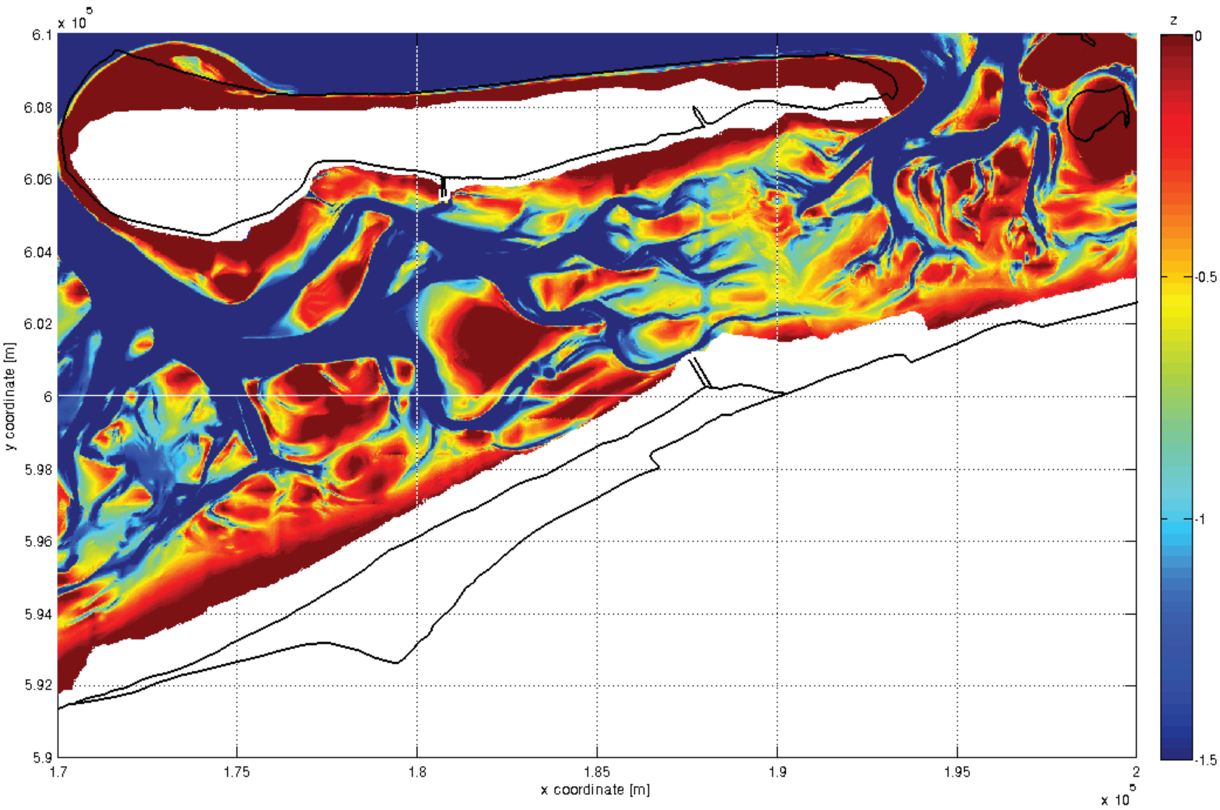
Ameland 1981



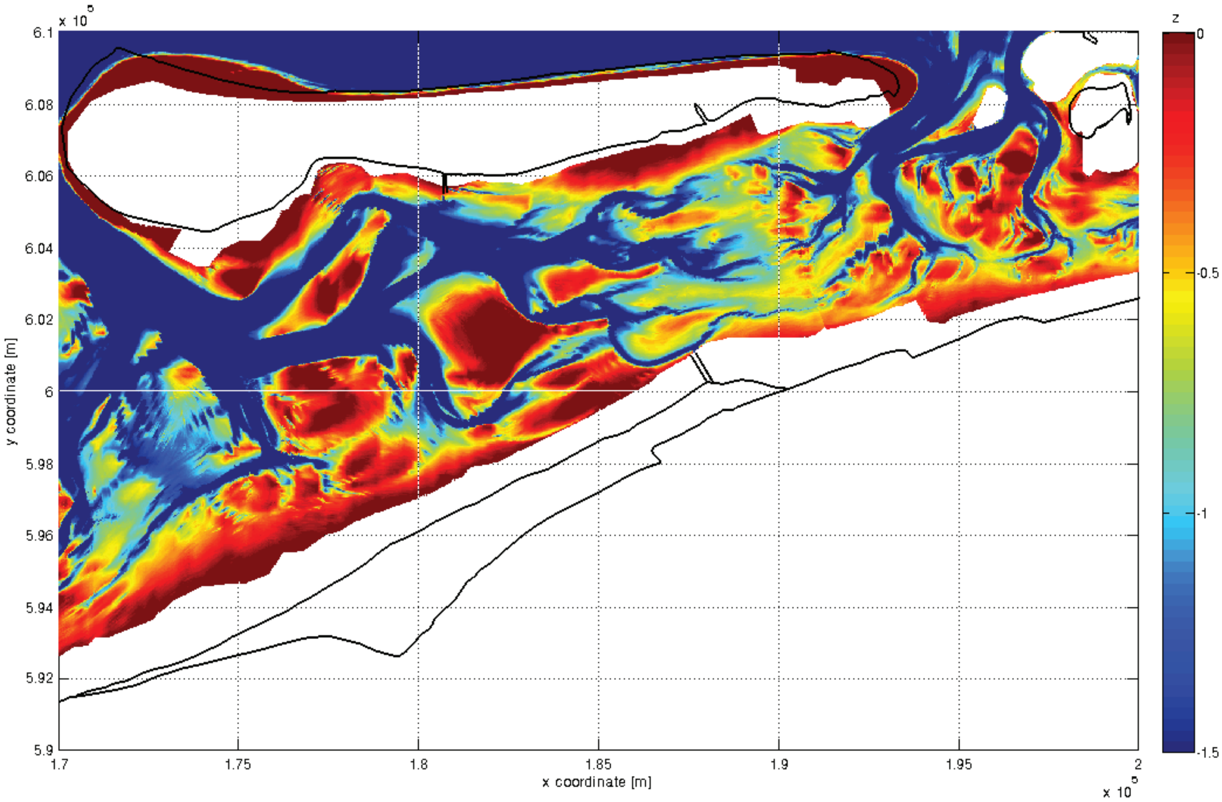
Ameland 1989



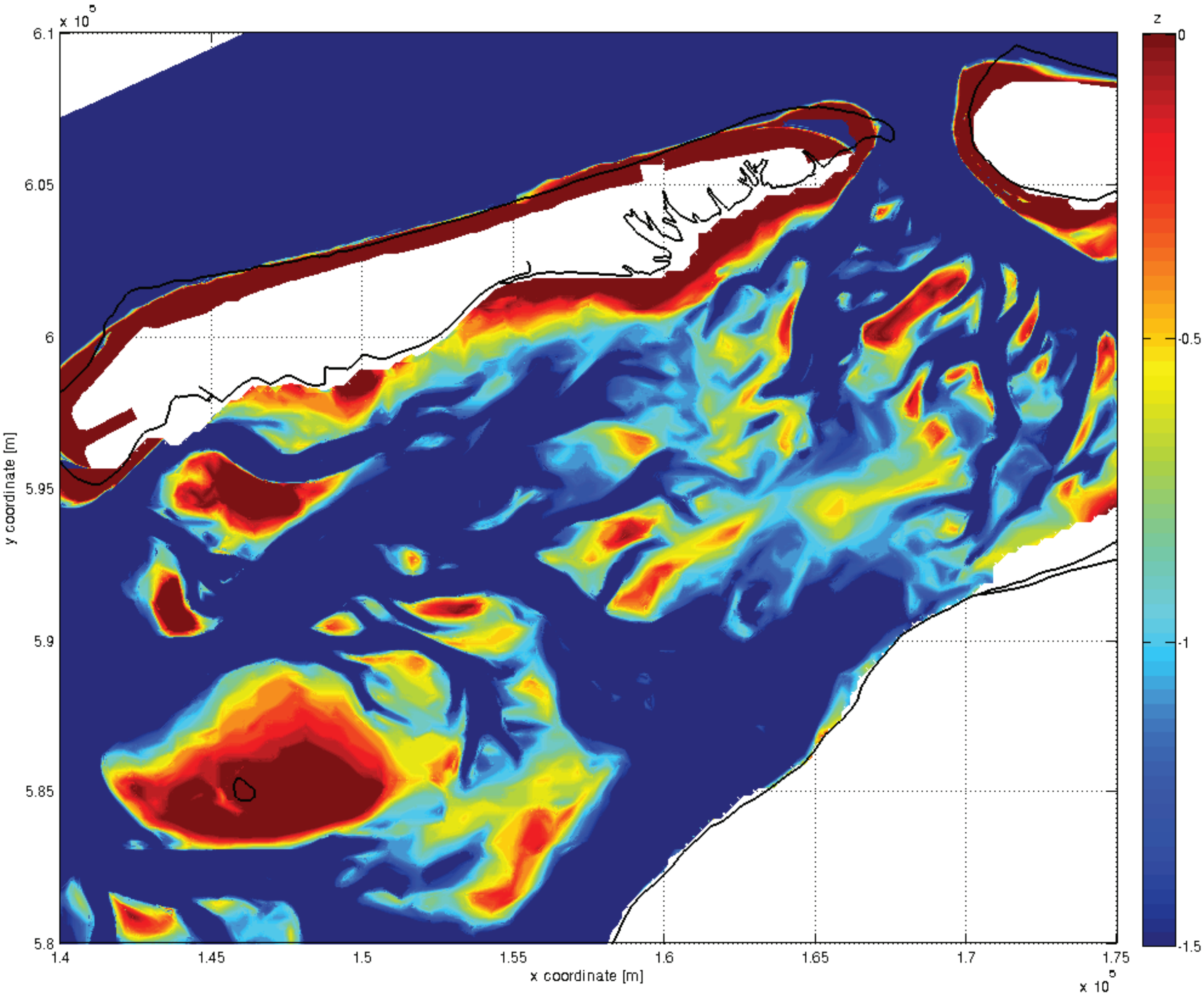
Ameland 1993



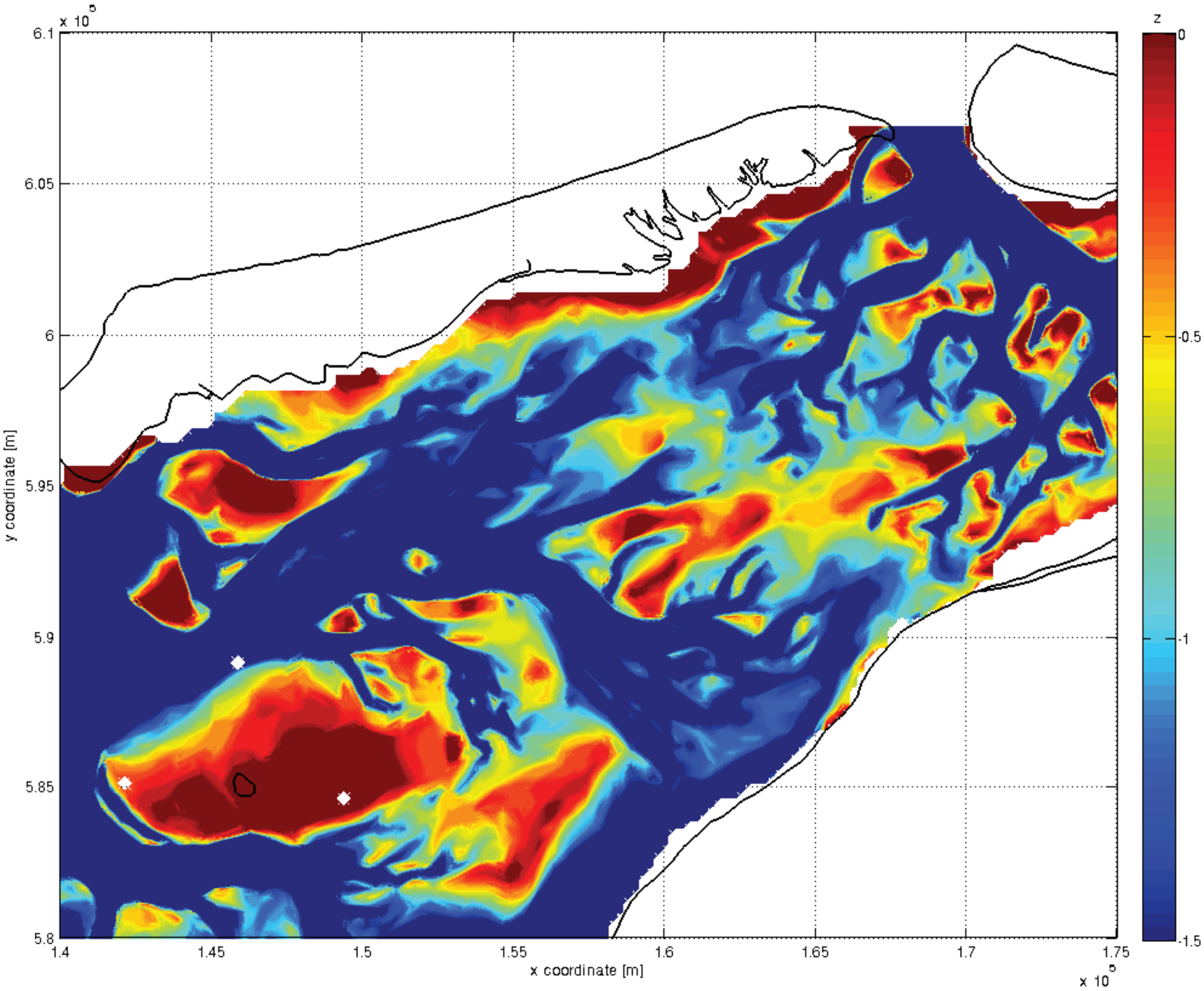
Ameland 1999



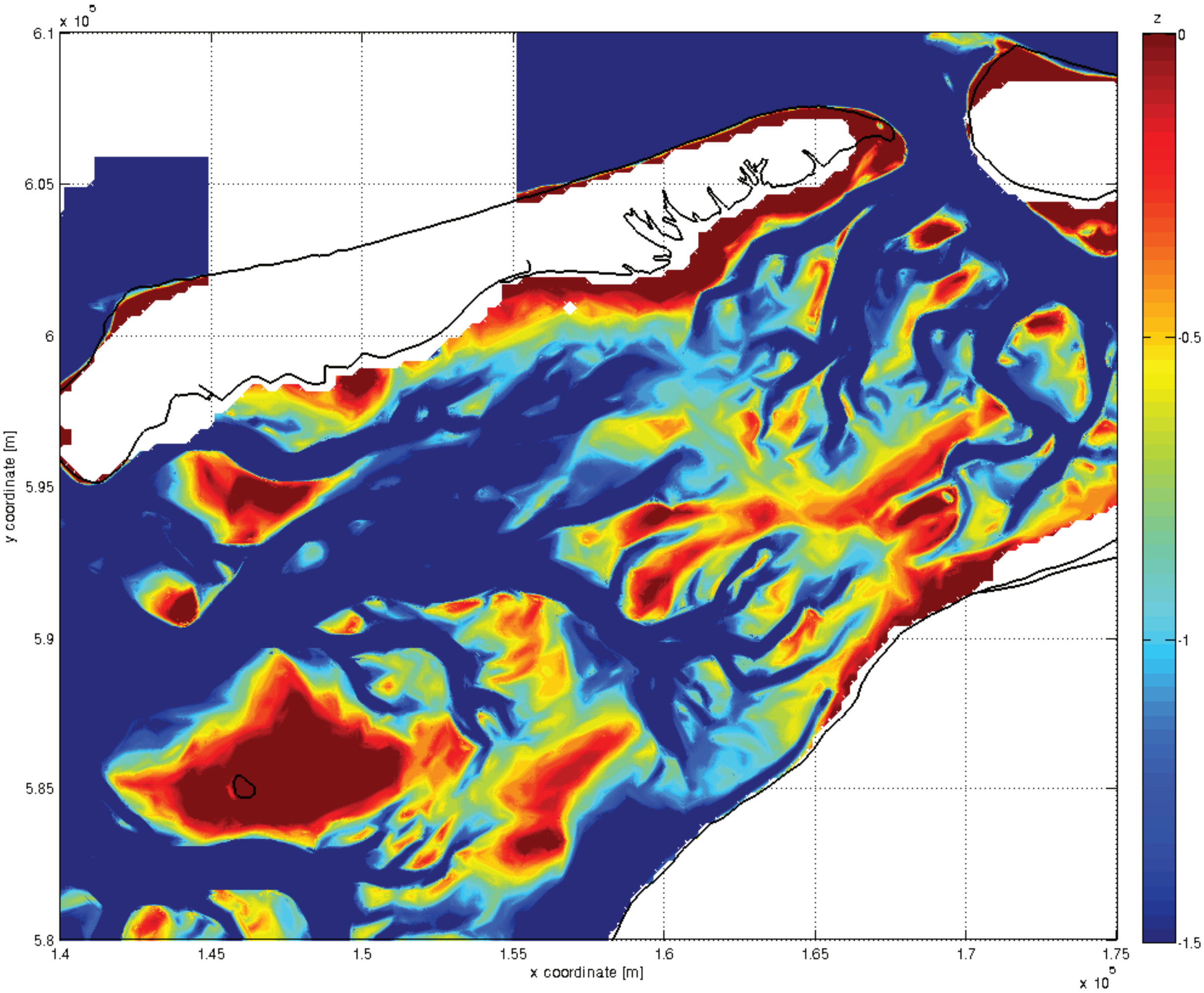
Ameland 2005



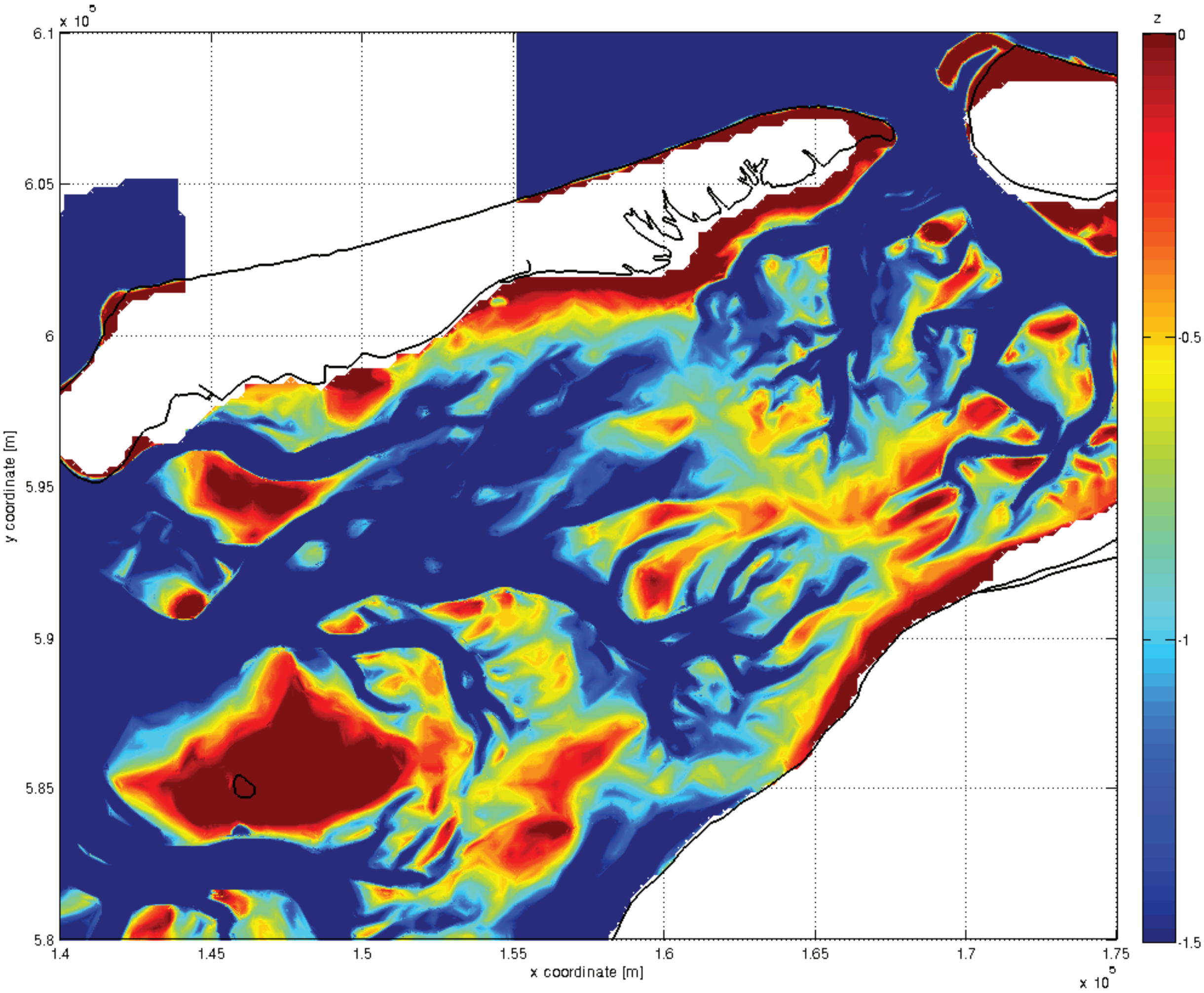
Terschelling 1926



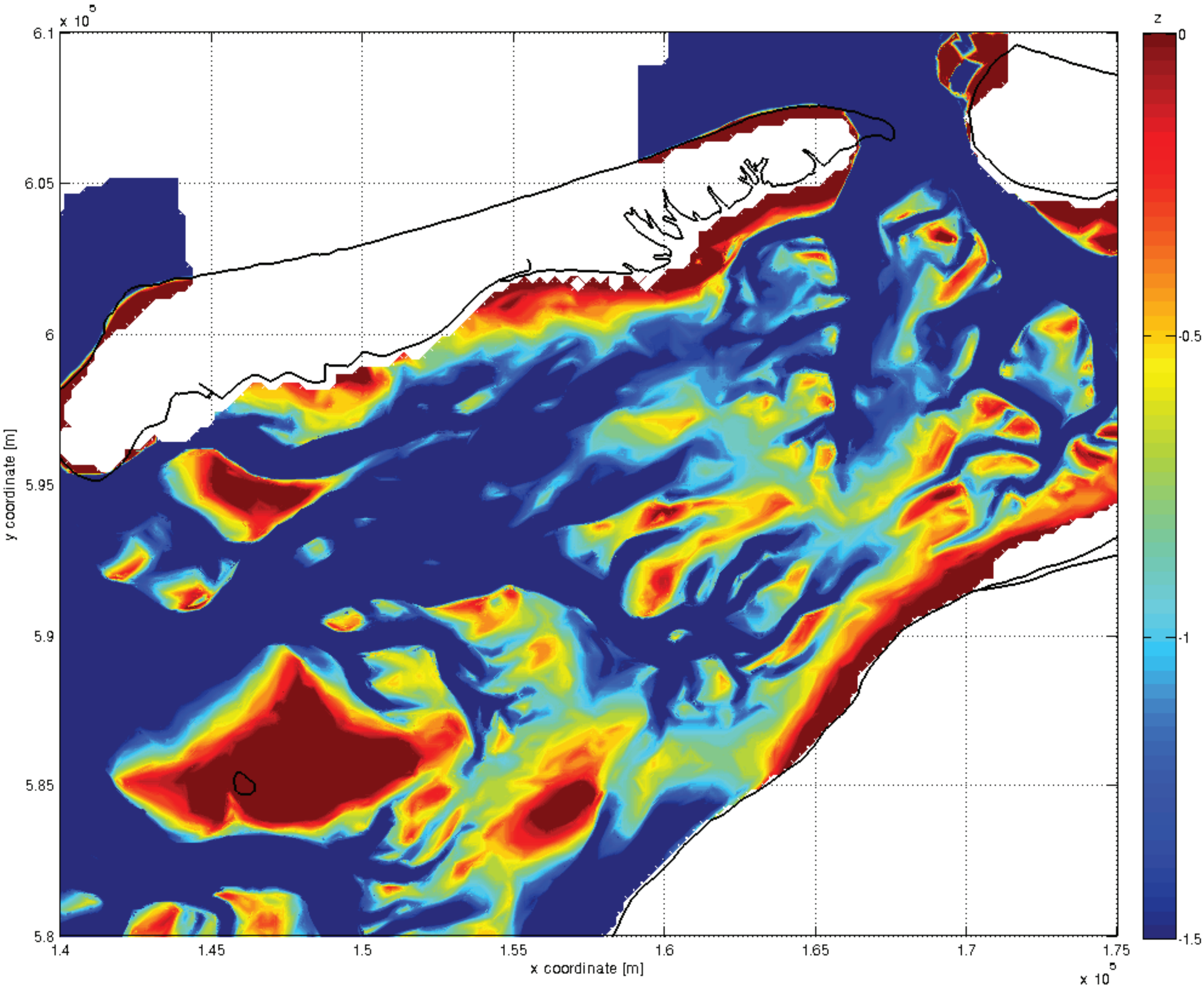
Terschelling 1948



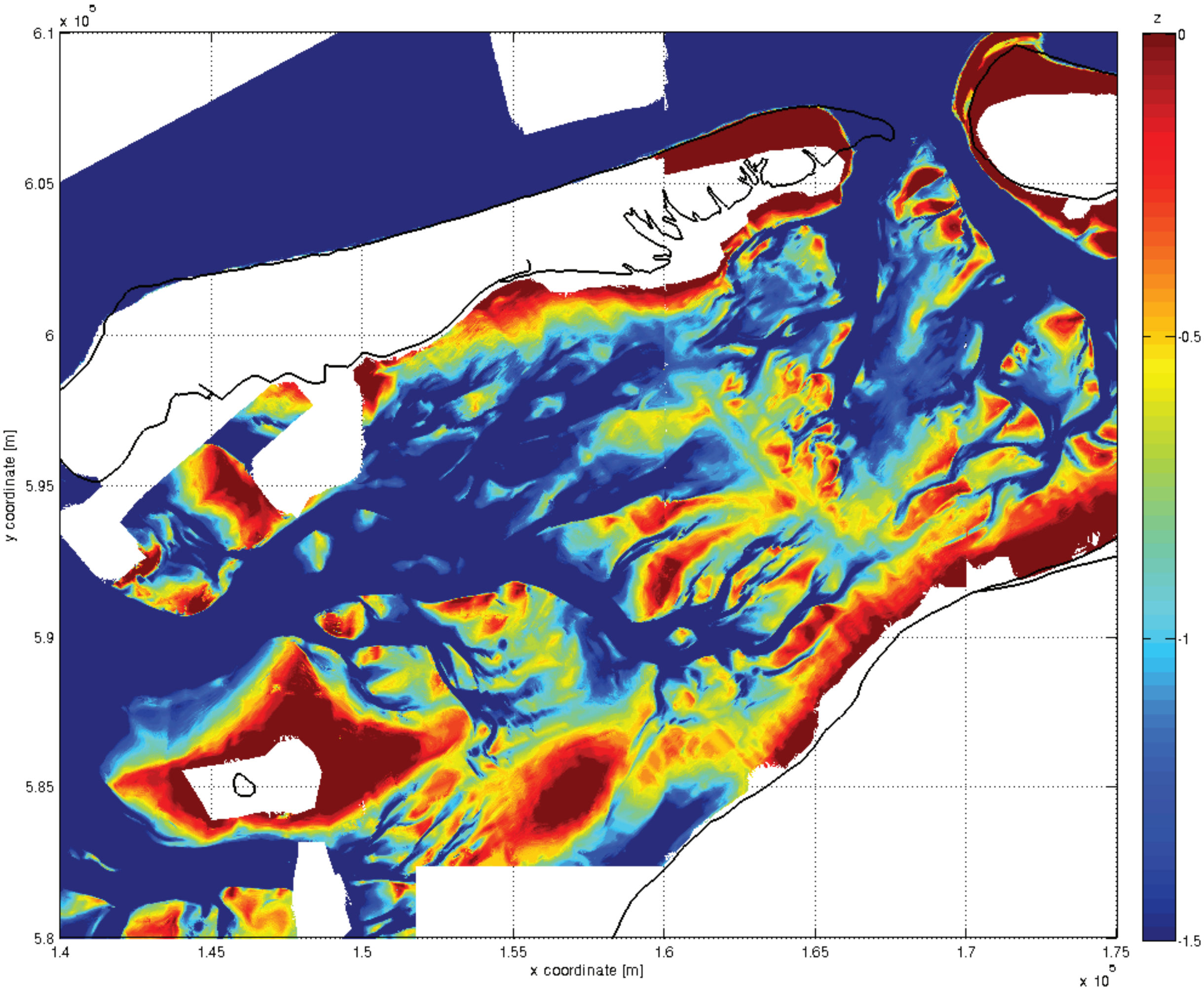
Terschelling 1971



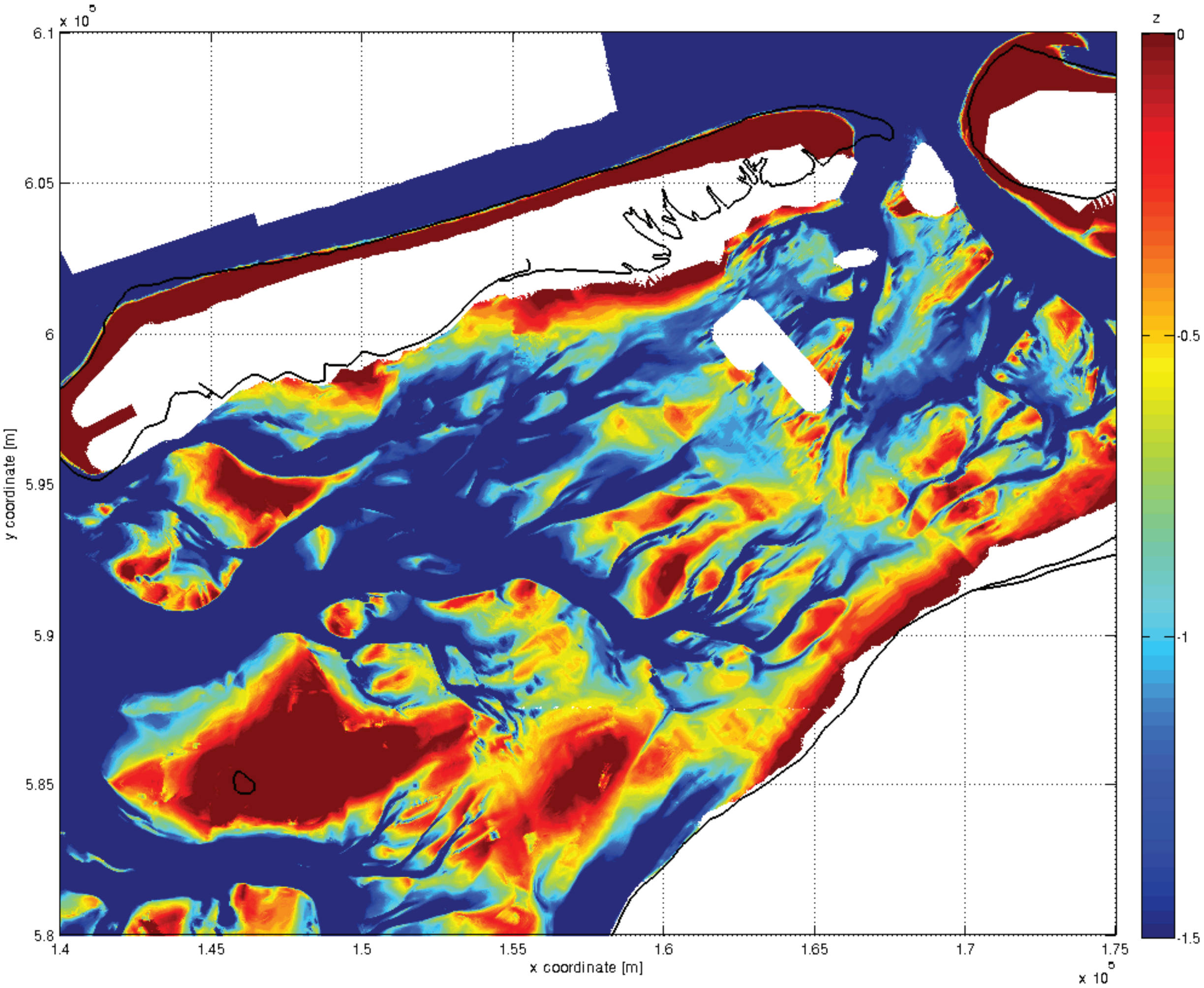
Terschelling 1975



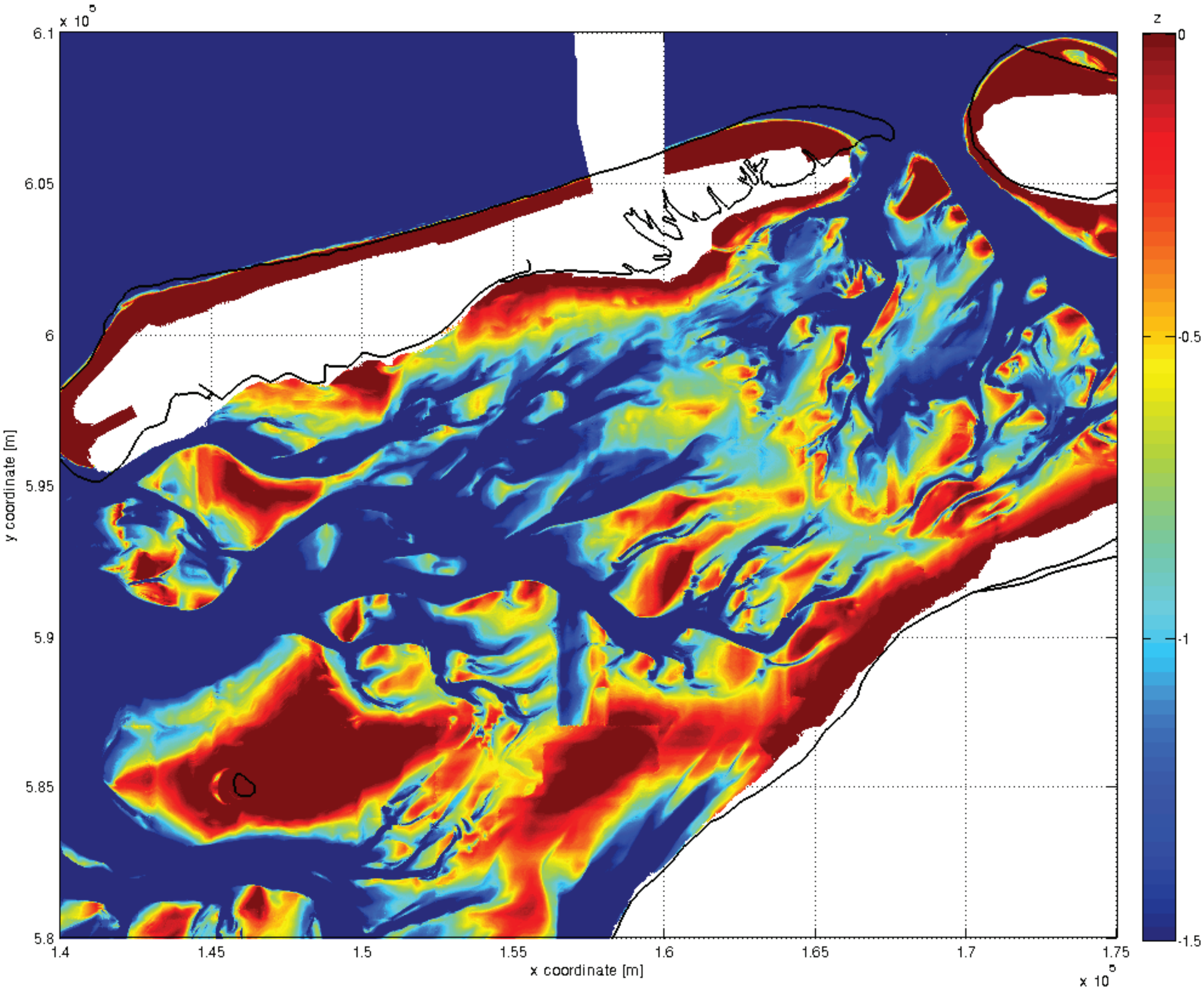
Terschelling 1981



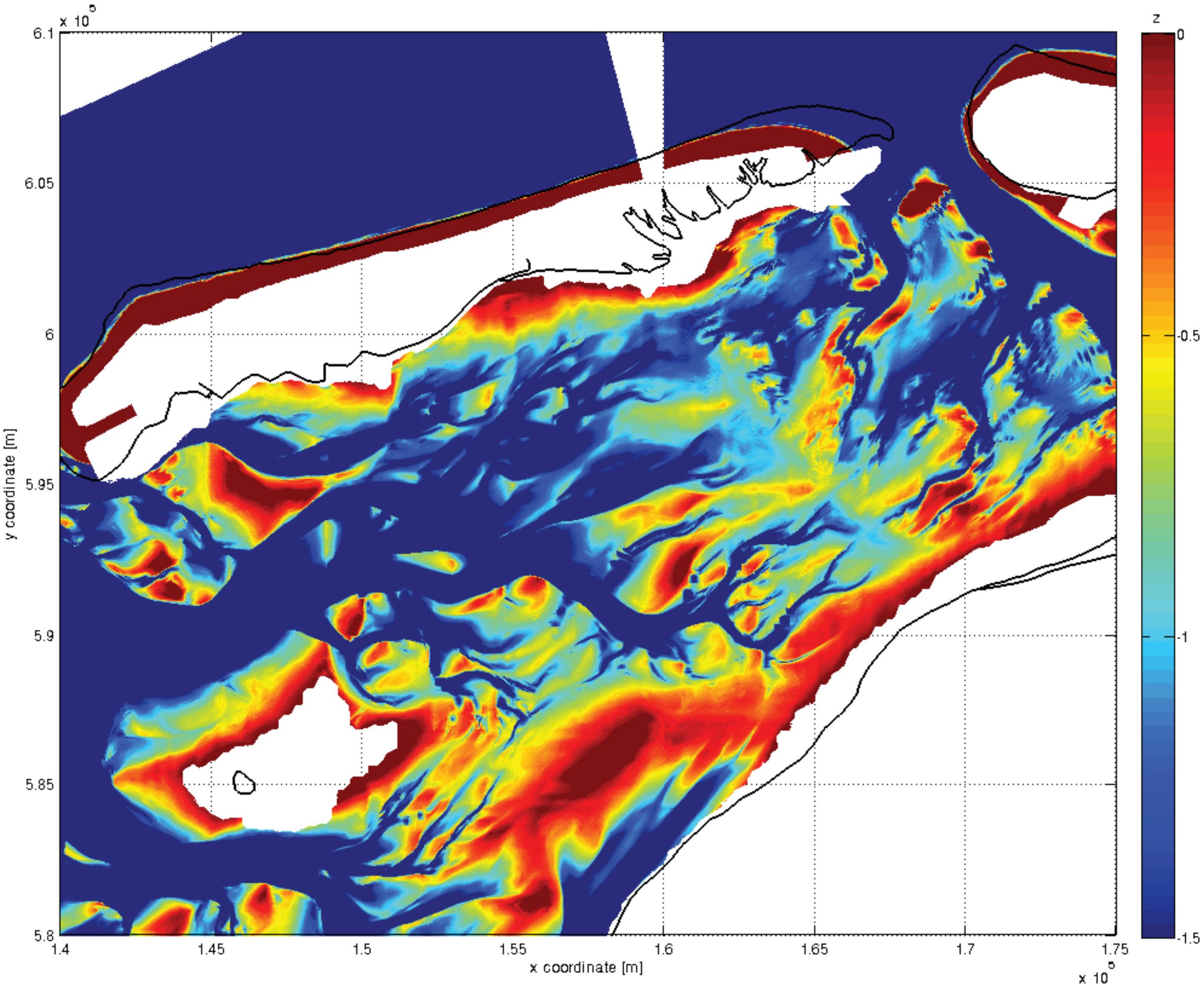
Terschelling 1988



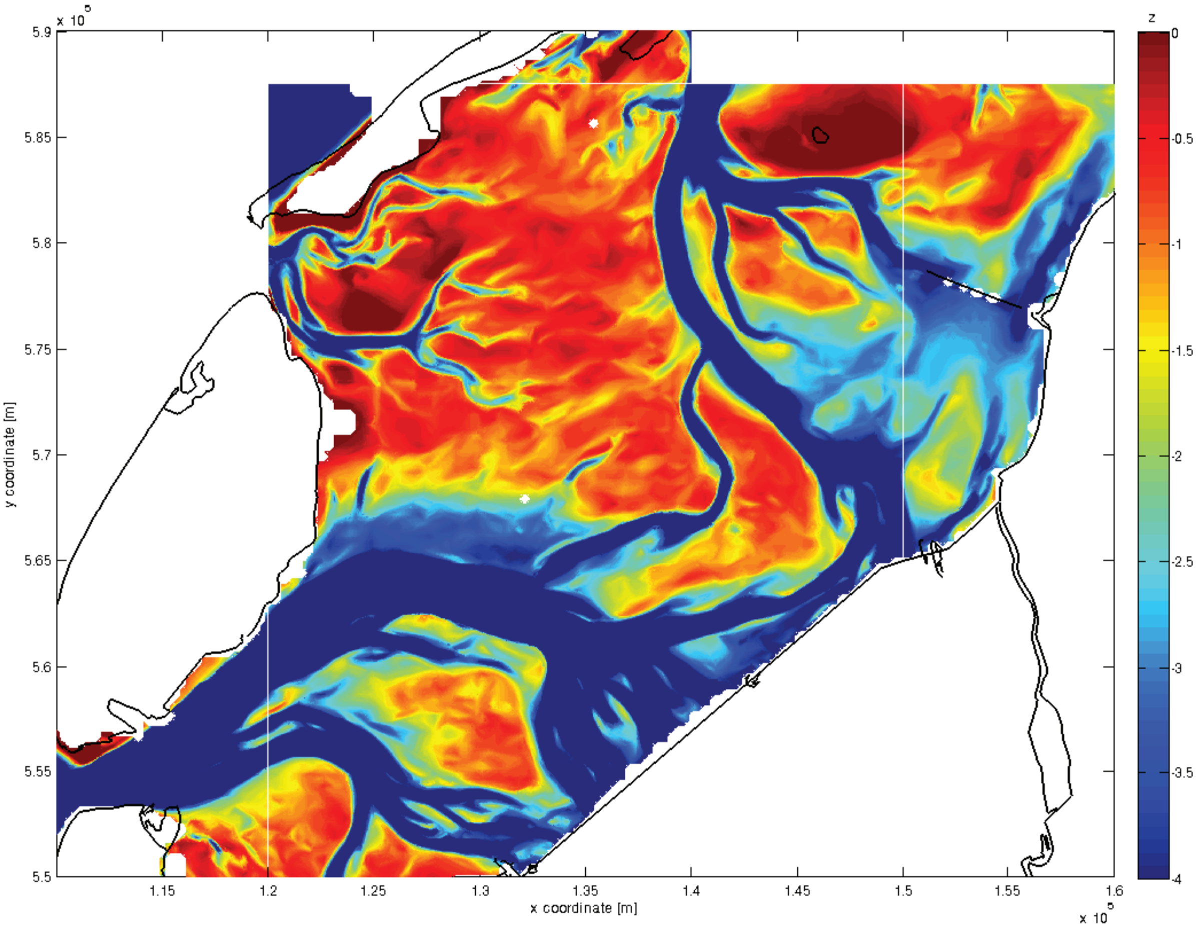
Terschelling 1992



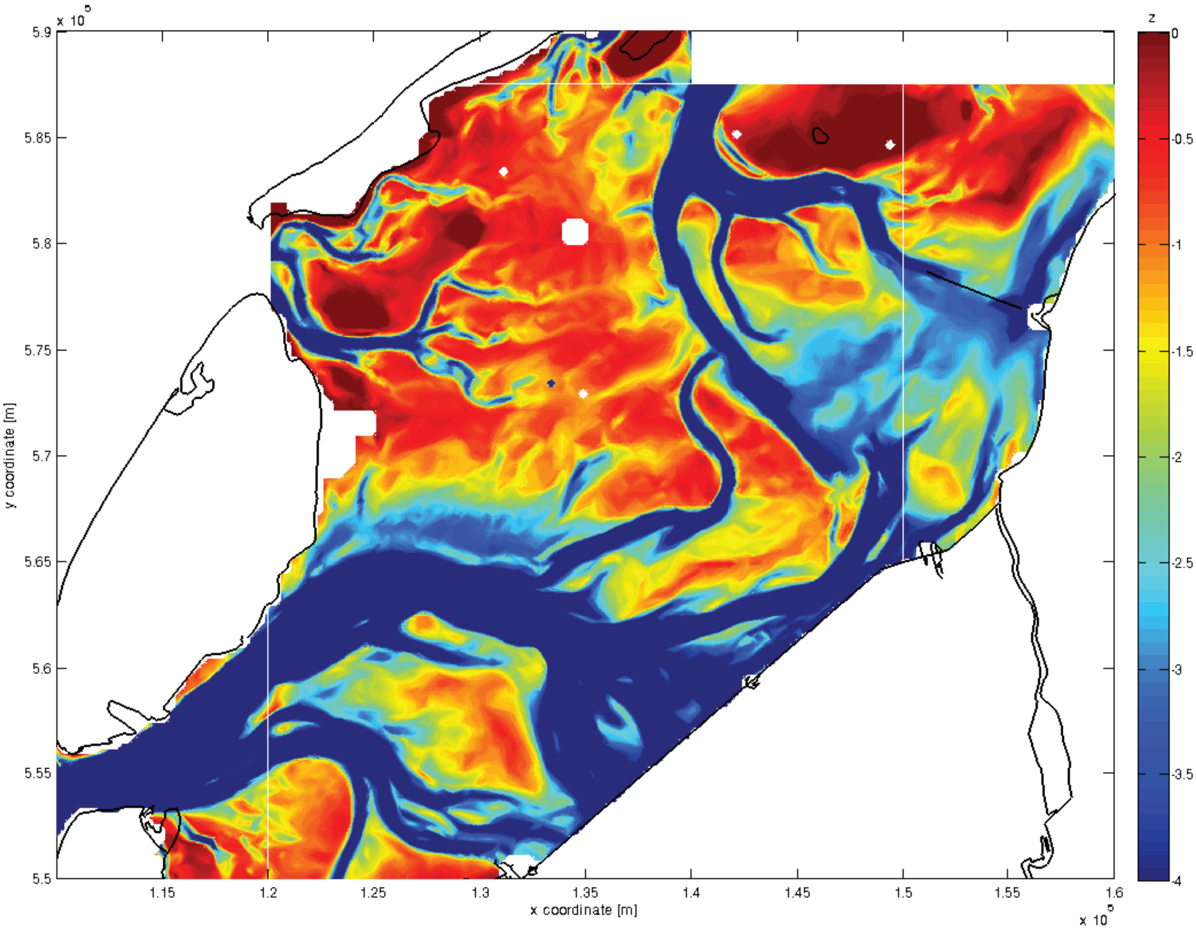
Terschelling 1998



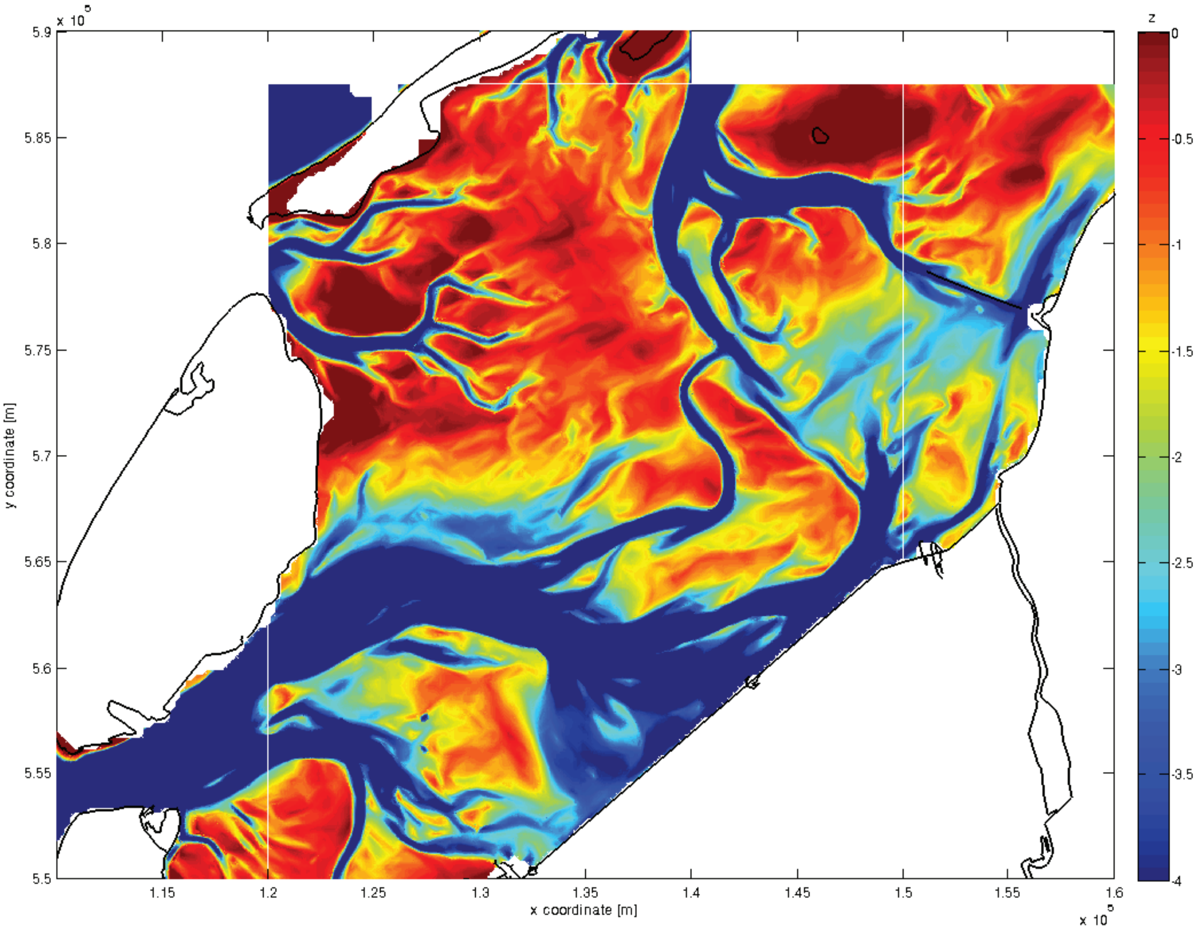
Terschelling 2004



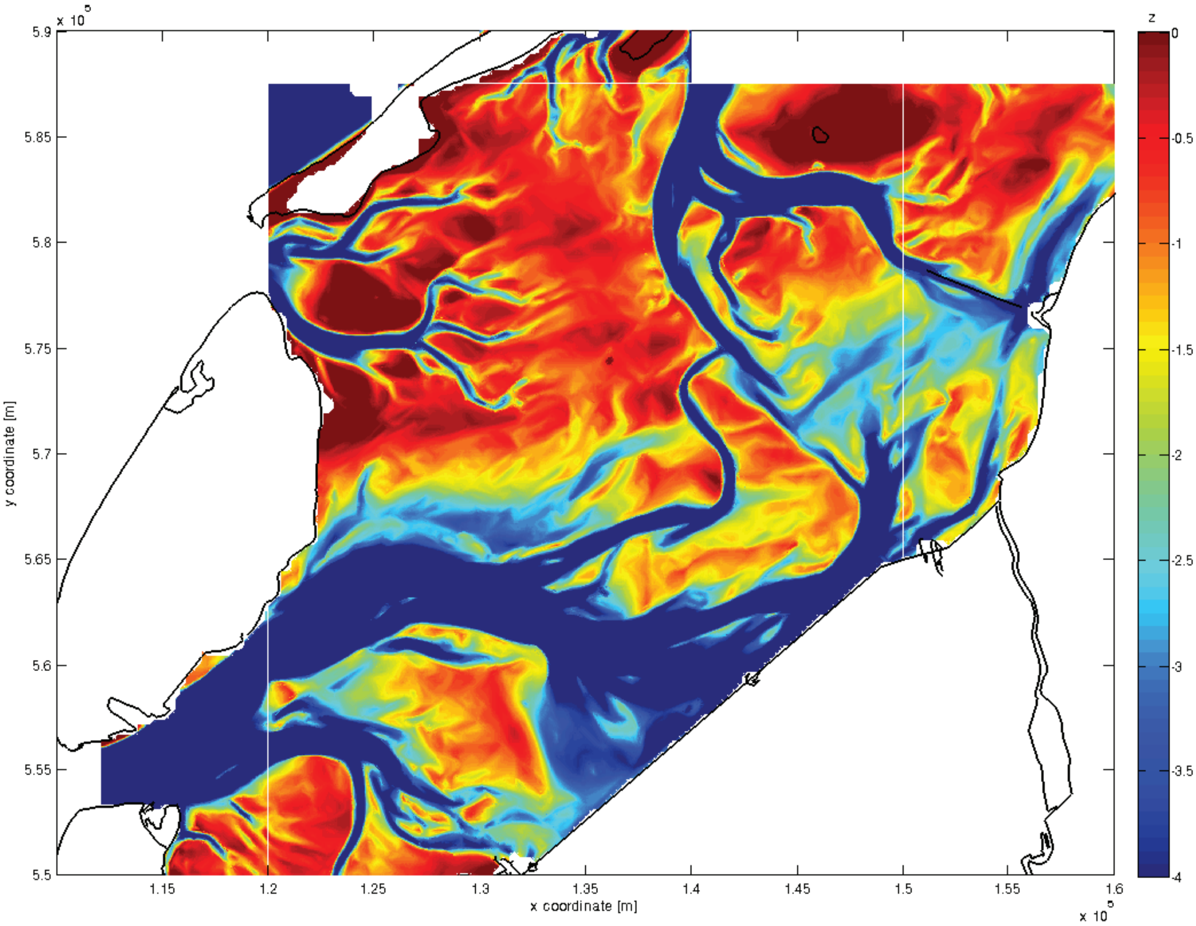
Western Wadden Sea 1926



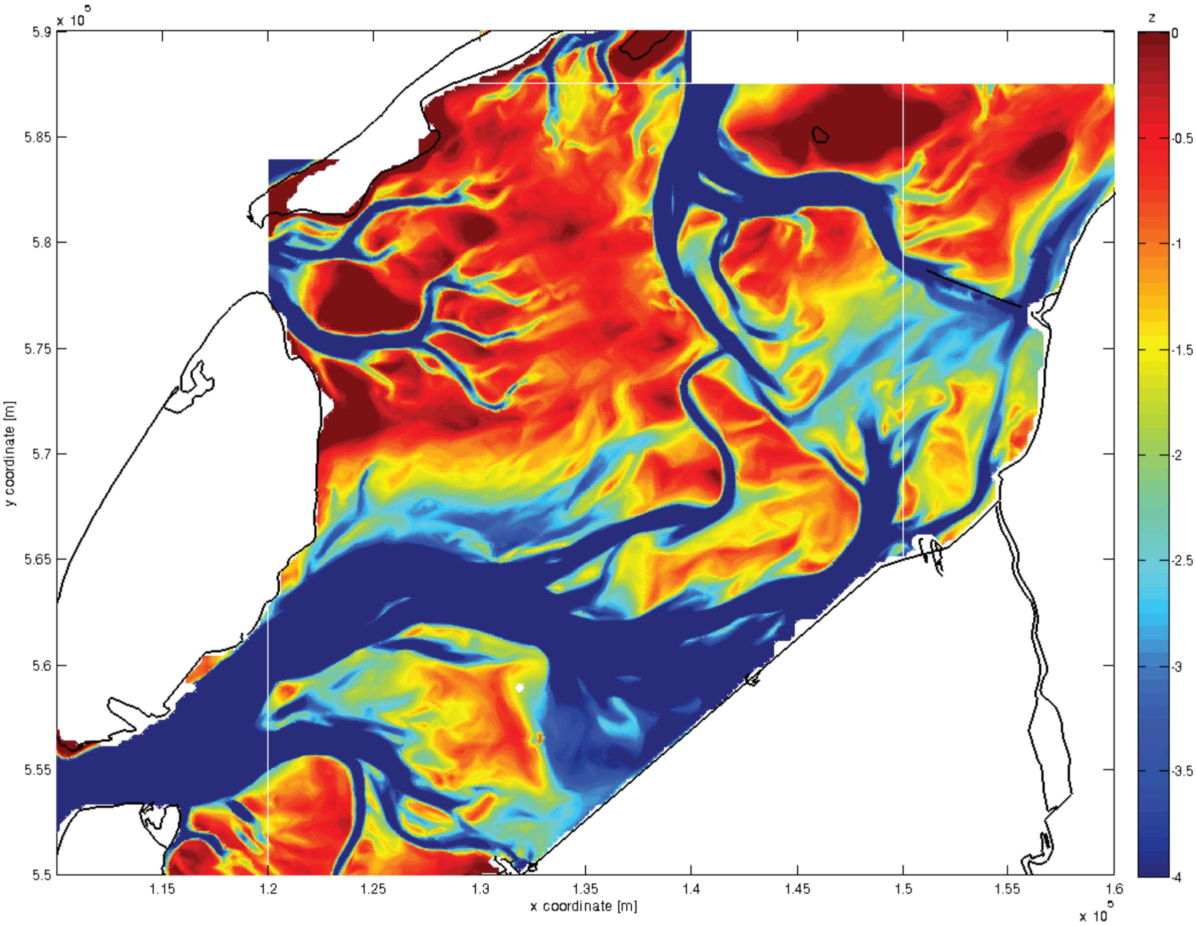
Western Wadden Sea 1948



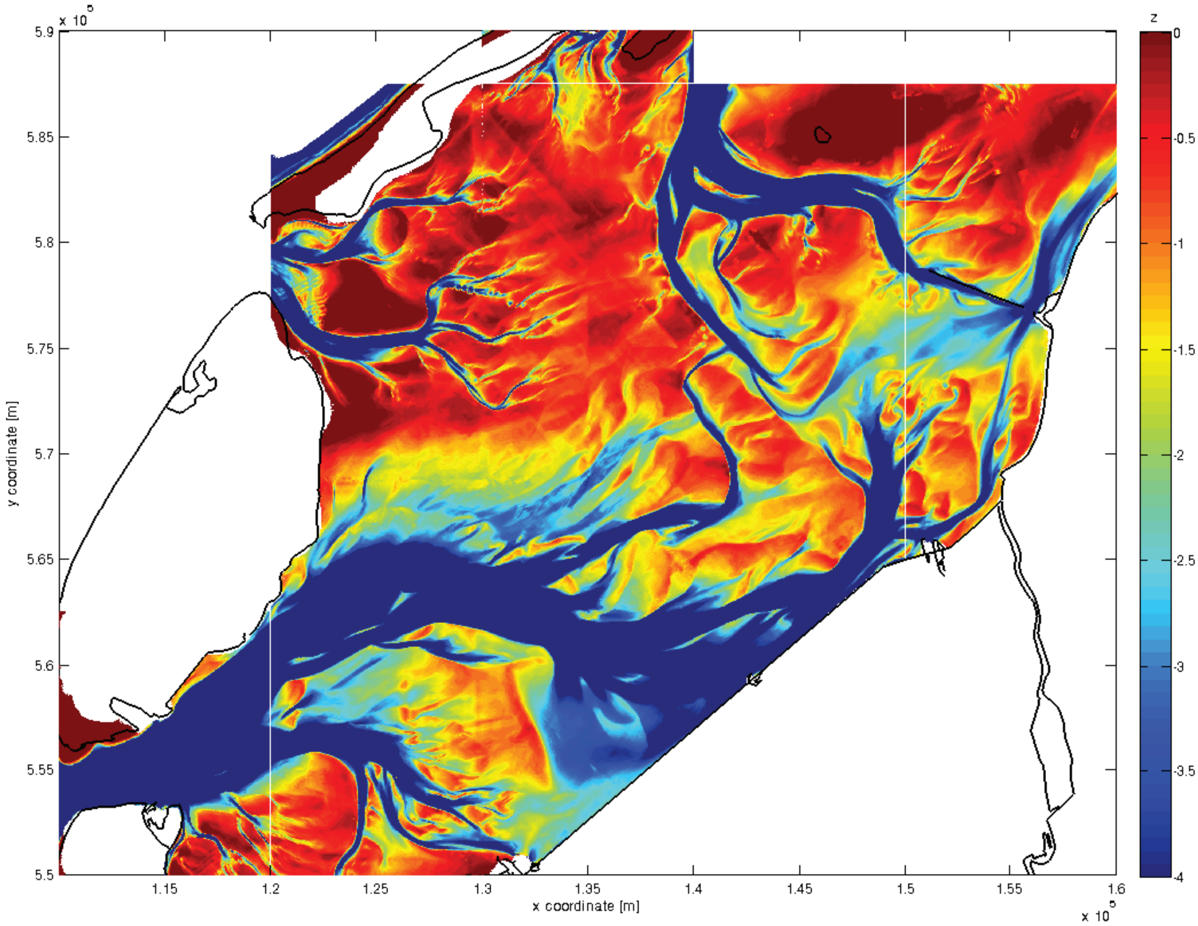
Western Wadden Sea 1971



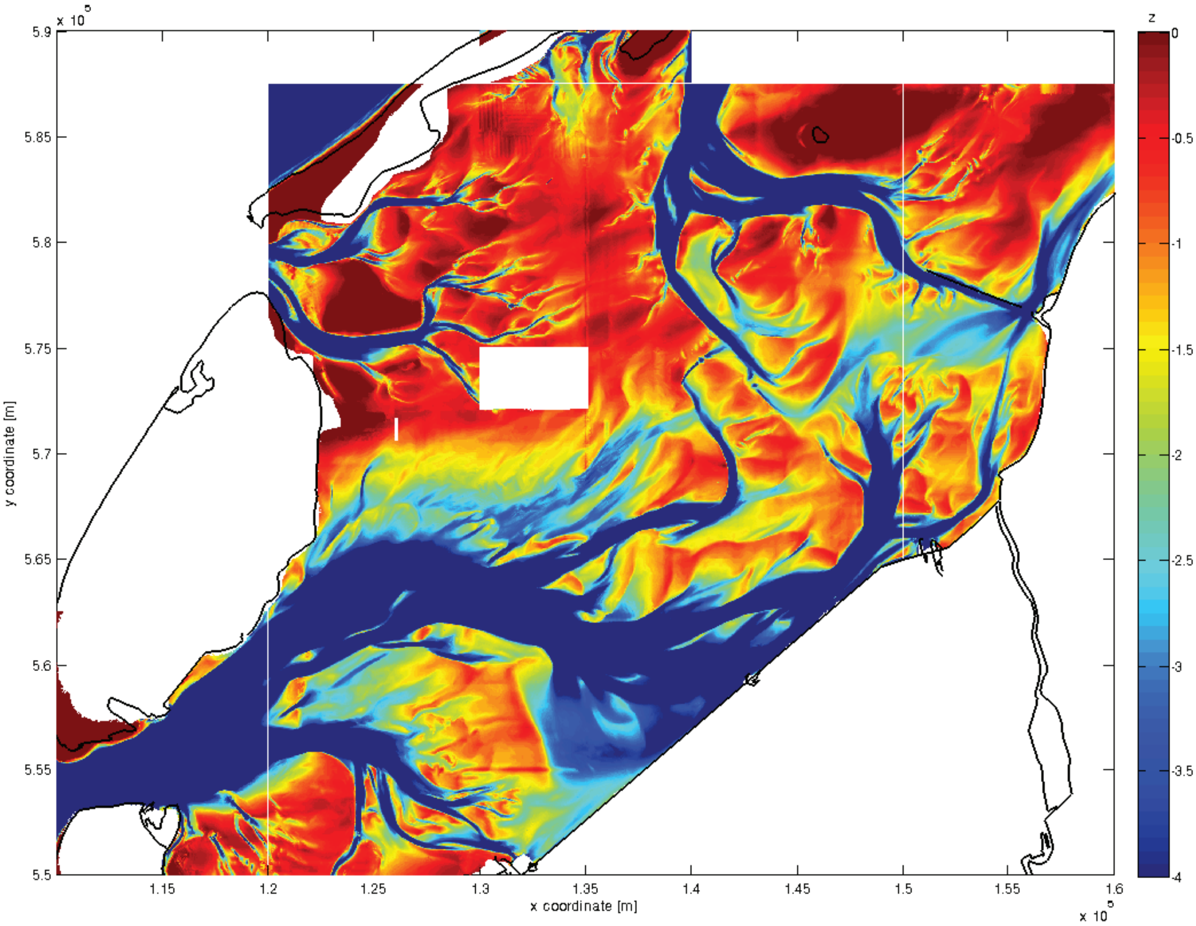
Western Wadden Sea 1975



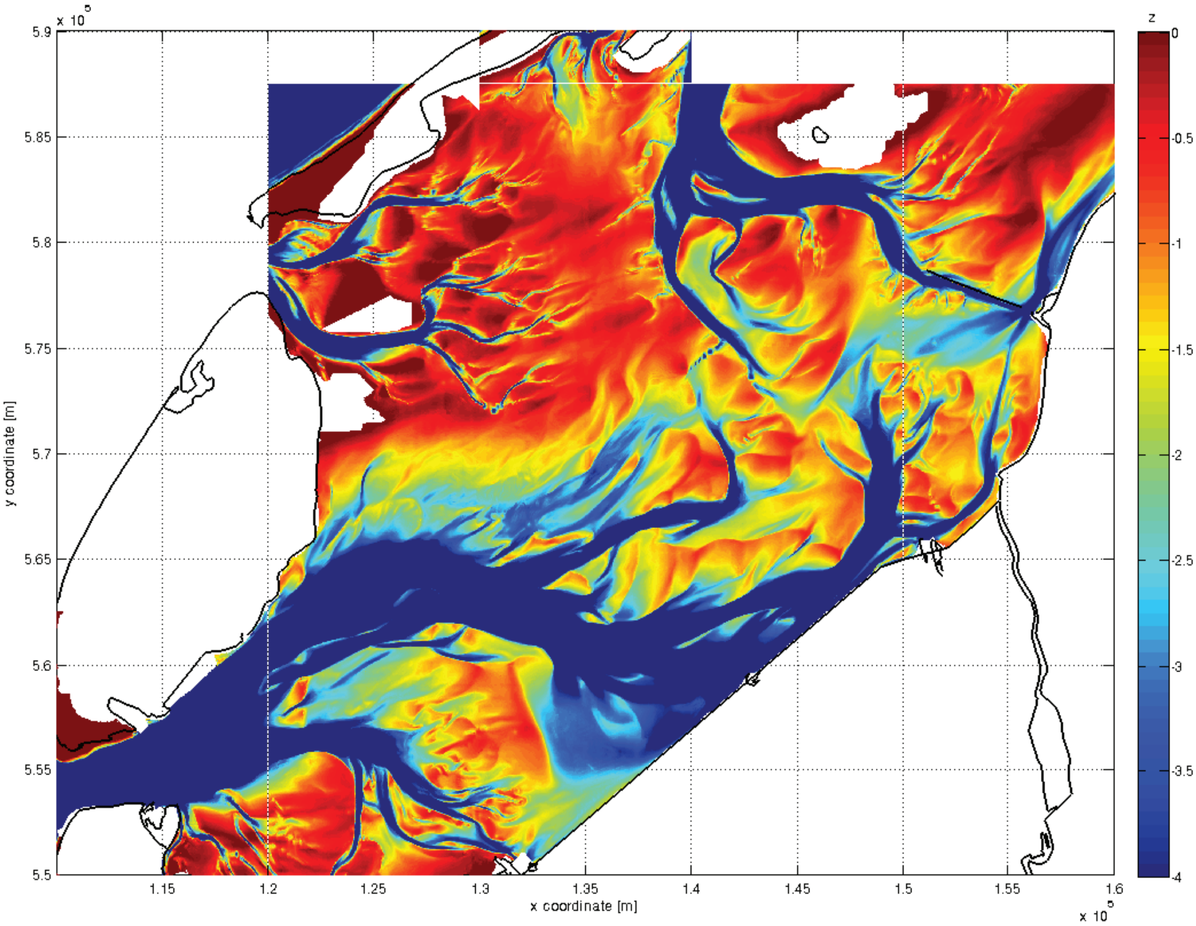
Western Wadden Sea 1981



Western Wadden Sea 1991



Western Wadden Sea 1998



Western Wadden Sea 2003